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## FABRICATION AND TESTING OF POLYVINYLLIDENE FLUORIDE CAPACITORS

JUNE 1980

AEROSPACE GROUPS

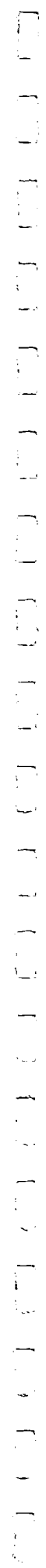
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| 16. Abstract<br>The objective of this program was to build and test high energy density capacitors made from metallized polyvinylidene fluoride film. Terminations of aluminum-babbitt, tin-babbitt, and all-babbitt were evaluated. All-babbitt terminations appeared to be better. The 0.1 $\mu$ F and 2 $\mu$ F capacitors were made of 6 $\mu$ m material. Capacitance, dissipation factor, and insulation resistance measurements were made over the ranges -55°C to 125°C and 10 Hz to 100 kHz. Twelve of forty-one 0.1 $\mu$ F capacitors survived a 5000-hour DC plus AC life test. Under the same conditions, the 2 $\mu$ F capacitors exhibited overheating because of excessive power loss. Some failures occurred after low temperature exposures for 48 hours. No failures were caused by vibration or temperature cycling. |  |  |  |  |  |
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FABRICATION AND TESTING OF  
POLYVINYLIDENE FLUORIDE CAPACITORS

Contract No. NAS 3-21042

June 1980

Electro-Optical and Data Systems Group  
AEROSPACE GROUPS  
Hughes Aircraft Company • Culver City, California



**NASA  
FORMAL  
REPORT**





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## FOREWORD

This report documents all work performed by the Hughes Aircraft Company during the period 27 September 1977 to 30 May 1980 for NASA Lewis Research Center under Contract NAS3-21042. The NASA Project Manager at Lewis Research Center was Thomas J. Riley. The Program Manager at Hughes Aircraft Company was Robert S. Buritz.





## ABSTRACT

The objective of this program was to build and test high energy density capacitors made from metallized polyvinylidene fluoride film. Terminations of aluminum-babbitt, tin-babbitt, zinc-babbitt, and all-babbitt were evaluated. All-babbitt terminations appeared to be better. The  $0.1\ \mu\text{F}$  and  $2\ \mu\text{F}$  capacitors were made of  $6\ \mu\text{m}$  material. Capacitance, dissipation factor, and insulation resistance measurements were made over the ranges  $-55^{\circ}\text{C}$  to  $125^{\circ}\text{C}$  and 10 Hz to 100 kHz. Twelve of forty-one  $0.1\ \mu\text{F}$  capacitors survived a 5000 hour DC plus AC life test. Under the same conditions, the  $2\ \mu\text{F}$  capacitors exhibited overheating because of excessive power loss. Some failures occurred after low temperature exposures for 48 hours. No failures were caused by vibration or temperature cycling.

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## I. INTRODUCTION

Much research and development has been done in the past 15 years to decrease the size and weight of electronic components for spacecraft power converters. This effort has been directed primarily at transformers, which are the largest and least efficient components. Since not as much effort had been focused on capacitors, the state-of-the-art capacitors, on the basis of weight and volume, were the least efficient components. Present and foreseeable systems dictate filter and commutator capacitor ratings of a few microfarads at voltages between 500 V and 2 kV.

Under two recent contracts, Hughes has developed metallized film capacitors rated at 2  $\mu$ F 500 V with improved energy density. Testing to a considerable extent was limited. The present program was a follow-on "to test and operate these capacitors under extreme environmental and operational conditions to determine their operational limits."

### PRIOR CONTRACTS

Under Contract No. NAS3-18925 for the NASA Lewis Research Center, completed in 1976, Hughes developed ultra lightweight metallized film capacitors rated at 2  $\mu$ F 500 VDC with an energy density greater than 0.1 joules/gram (Ref. 1). This energy density was approximately 10 times greater than that of capacitors previously available for the same operating conditions. The small size and low weight of these capacitors was achieved through the use of polyvinylidene fluoride film (PVF2) and through the use of higher electric field stresses. This film has a high dielectric constant of 11 as compared to 3.5 for most other capacitor films. In addition, a lightweight case design was developed for this capacitor.

The voltage at which these new high energy density capacitors could operate was limited by the quality of the film and of the manufacturing process. It has been shown repeatedly that the intrinsic dielectric strength of a polymeric film is between  $4.8 \times 10^6$  V/cm (12 kV/mil) and  $7.2 \times 10^6$  V/cm (18 kV/mil). Operating a film capacitor at  $4.8 \times 10^6$  V/cm could achieve an energy density of 2.5 J/gram. In practice, however, the energy density is limited by the available thickness of the film and by flaws in the

dielectric. Furthermore, most manufacturing processes yield components so imperfectly configured that they fail well below the voltage limitations of even the imperfect dielectric.

Testing of these capacitors was limited to parameter measurements and a 2500-hour life test.

A second Contract No. NAS3-20090, for the NASA Lewis Research Center, was completed in 1977 to develop cylindrical wound metallized film capacitors (Ref. 2). PVF2 in 6  $\mu\text{m}$  thickness was employed in the final component. The capacitors were improved by removing certain conditions that were introduced during the manufacturing processes: in particular, the use of controlled winding tension, elimination of wrinkles, improved core design, and the reduction of particulate contamination. The cylindrical capacitors developed on this program were improved over previous parts.

The two NASA programs briefly described above were concerned with developing ultra lightweight cylindrically wound metallized film capacitors rated at 2  $\mu\text{F}$  500 VDC with an energy density greater than 0.1 J/gram. Polyvinylidene fluoride in 6  $\mu\text{m}$  thickness was employed in the final components. Improved fabrication procedures were developed; however, testing of these capacitors was fairly limited. No attempt was made to characterize the components over their operating range or to establish failure rate, derating criteria, or other reliability information.

## PRESENT PROGRAM

This program was a follow-on that was intended to

1. Further the development of polyvinylidene fluoride capacitors
2. Apply technology from prior programs
3. Establish the capacitor characteristics for spacecraft and power conditioner use.

Briefly, the program consisted of an engineering effort to develop improved processing for flame sprayed end terminations, fabrication of one hundred and thirty 2  $\mu\text{F}$  capacitors and one hundred and thirty 0.1  $\mu\text{F}$  capacitors, electrical parameter measurements, and testing. The latter included low temperature, 10,000-hour life at elevated temperature, thermal cycling and vibration. The flow chart of the test program is shown in Figure 1.

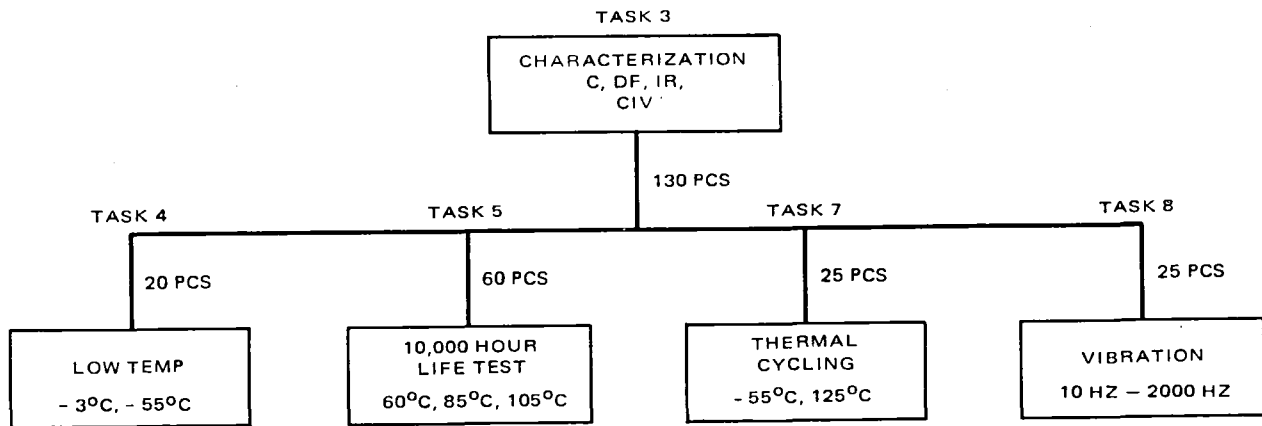


Figure 1. Test program flow chart.

The program was divided into a series of eight tasks as summarized below.

#### Termination Investigation

Methods previously and presently used for the fabrication of metallized film capacitors were examined. Procedures documented in the final report from the prior program were employed (see NASA CR13586).

The effect of using babbitt with other metals for end terminations was investigated. The parts were evaluated by being subjected to  $10^5$  high current pulses of  $400 \text{ A/cm}^2$ . Additional tests were conducted at higher currents of 600, 800 and  $1000 \text{ A/cm}^2$ .

#### Capacitor Fabrication

Using approved procedures, one hundred and thirty  $2 \mu\text{F}$  and one hundred and thirty  $0.1 \mu\text{F}$  capacitors were fabricated for evaluation. Metallized polyvinylidene film  $6 \mu\text{m}$  thick was used for both types of capacitors.

Winding procedures included a method to control the film tension. Also, a number of techniques were examined for starting the winding that would be applicable for production.

#### Capacitor Characteristics

Capacitance, dissipation factor, and insulation resistance, were measured for each of the 130 capacitors of each type.

### Low Temperature Tests

The characteristics of 20 capacitors of each type at  $-3^{\circ}\text{C}$  and  $-55^{\circ}\text{C}$  were determined.

### Life Test

Sixty capacitors of each type were subjected to a 5000-hour life test at  $105^{\circ}\text{C}$ ,  $85^{\circ}\text{C}$ , and  $60^{\circ}\text{C}$  at voltages of 500 VDC plus 10 VAC at 10 kHz.

### Thermal Cycling

Twenty-five capacitors of each type were subjected to temperature cycling from  $-55$  to  $+125^{\circ}\text{C}$ .

### Vibration Tests

Twenty-five capacitors of each type were subjected to vibration of 20 g peak at a maximum vibration amplitude of 0.06 inch double amplitude.

### Failure Analysis

Failed capacitors were analyzed to determine the nature and cause of failure.

Each of these tasks is discussed in a chapter in the body of this report.

## II. TERMINATION INVESTIGATION

### FLAME SPRAYING

Flame sprayed metal is the conventional end termination and electrical connection used for metallized film capacitors. The process of flame spraying is well known and has many applications (Ref. 3). A typical gun and installation suitable for capacitors is shown in Figures 2 and 3. The metal to be sprayed is fed into the gun where it is melted in the nozzle with a flame of burning gas. The actual flame is used for melting and does not in itself spray metal. The flame must be surrounded with a stream of compressed gas that disintegrates the film of molten metal as it forms. To obtain adequate melting with a fine spray, the design of the nozzle is critical. Acetylene gas and oxygen are used for the flame and air for the spray. Regulators and flow meters are used to control the gas pressure and flow rate.

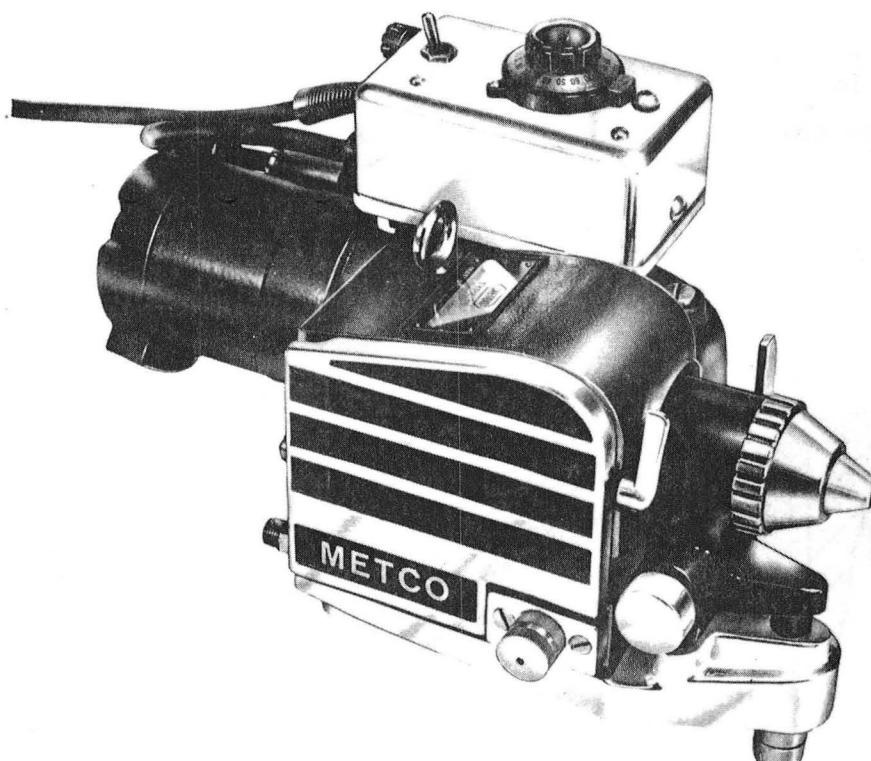


Figure 2. Metal spray gun.

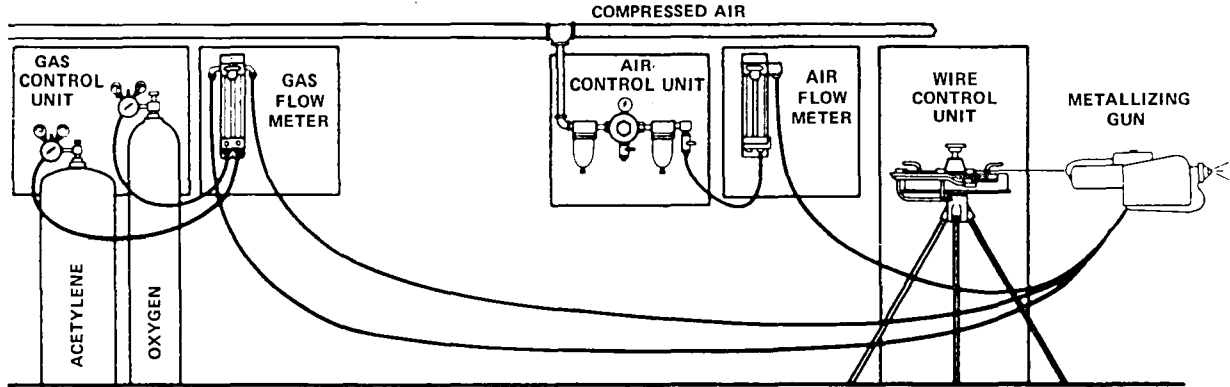


Figure 3. Typical installation for flame spraying.

In a common construction, the entire end of the capacitor is sprayed with metal as shown in Figure 4. The contact resistance between the end sprayed metal and the metallization on the film is extremely important when the capacitor is used in high frequency AC or pulsed circuits, since this resistance will contribute significantly to the total dissipation of the capacitor. Because the contact is concentrated in a small area, a poor contact often results in localized heating and subsequent failure of the capacitor. In a typical lot of 0.2  $\mu\text{F}$  capacitors received from a vendor, the dissipation factor, DF, ranged from 3.5 to 13.5 percent when measured at 20 kHz. The high DF was caused by poor contact between the end spray and the film metallization.

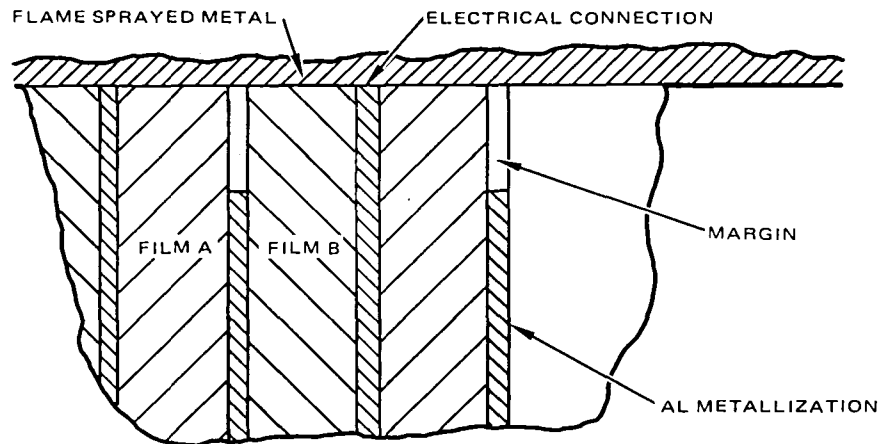


Figure 4. Detail of metalized film connections.



The method usually used in applying the metal to the ends of the capacitors is to have the gun in a fixed position. The operator holds the capacitors in one hand and moves them back and forth in front of the gun. Alternately, the gun may be moved back and forth with the capacitors in a fixed position as in paint spraying. In either case, the process is dependent entirely on the skill and judgement of the operator.

Hughes has developed an improved method in which the capacitor is rotated in a chuck positioned a fixed distance in front of the metal spray gun that is stationary. The spraying time is predetermined and closely controlled. This process combined with close control of the margin and offset of the winding has resulted in better terminations for high current applications. In addition, winding with the metallization on the outside gives a much lower termination resistance.

The method for flame spraying described above was limited to spraying one piece at a time. A further disadvantage was that the flame spray gun had to be started for each piece. With the improved method, shown in Figure 5, a number of terminations could be sprayed at one time. This scheme was used for making the capacitors for the test program and some of the resistivity specimens tested at high current.

## IMPROVED TERMINATIONS

Prior Hughes sponsored development work to improve the terminations utilized resistivity specimens. Several lots of capacitor windings were wound with film that did not have margins, so the components after flame spraying were actually shorted. This configuration enabled direct measurements to be made of the termination resistance with a Kelvin resistance bridge. To test the windings, a power supply was developed that could apply short 1000 A current pulses at a low duty cycle.

Windings made by a capacitor manufacturer were tested and compared with windings made at Hughes. The latter were flame sprayed in cooperation with a metal spraying company. Testing consisted of applying high current pulses at low duty. Initial testing was at 100 amperes peak for 1000 cycles, then the current was increased in steps to 400 amperes that was reached at 7000 pulses. For the size windings used, 400 A

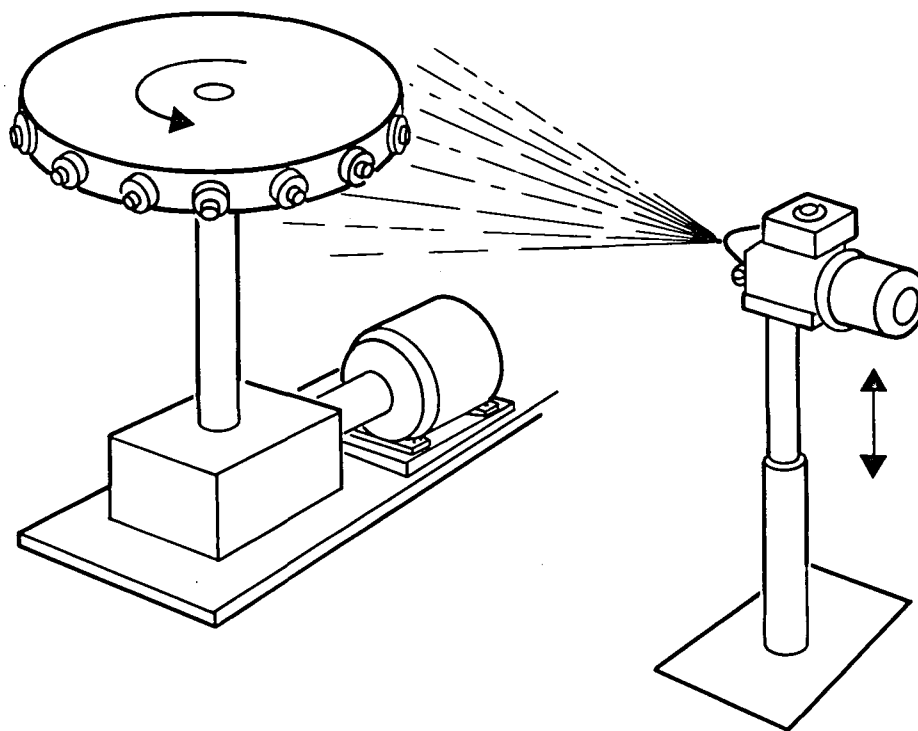


Figure 5. Scheme for controlling flame spraying.

was  $200 \text{ A/cm}^2$  of flame spray area. The testing continued at  $200 \text{ A/cm}^2$  for 162,000 pulses. A plot of the termination resistance versus number of pulses is shown in Figure 6. The resistivity of the terminations made by the capacitor manufacturer (old process) increased about 20 percent, which indicated a degradation of the electrical connection between the end spray and the film metallization. Finally, the current was increased to  $400 \text{ A/cm}^2$ , and the testing continued in the same manner. The windings made by the vendor failed within 1500 pulses. After 351,000 pulses, the Hughes windings continued to operate satisfactorily with insignificant change.

## TWO-METAL TERMINATIONS

The present contract extended the investigation of flame sprayed terminations to include other metals in combination with babbitt metal.

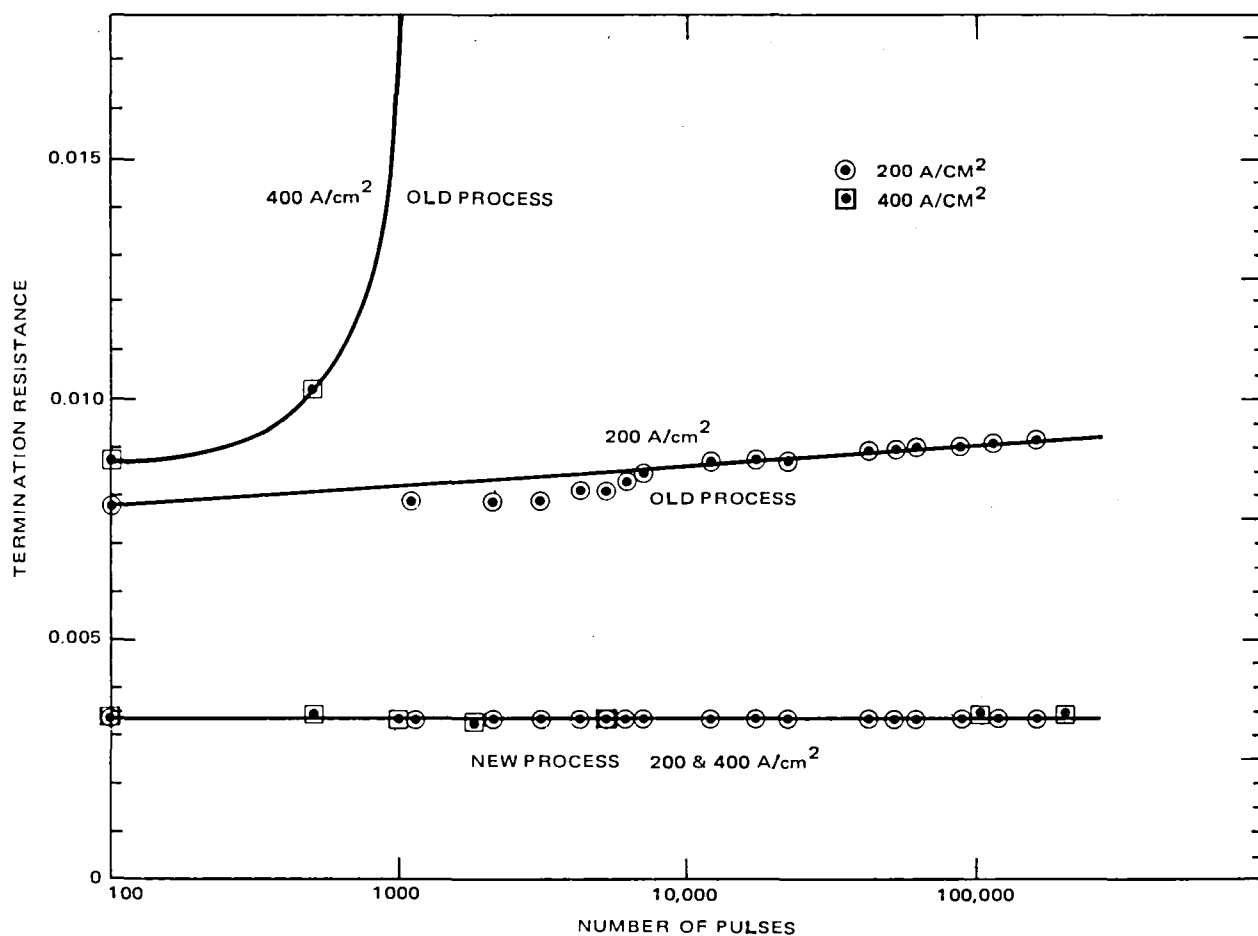


Figure 6. Change in termination resistance due to high current pulses.

Using 6  $\mu\text{m}$  metallized polyvinylidene fluoride film, 10 termination resistivity samples of each of the following combinations were fabricated.

1. 1 mil minimum aluminum + babbitt
2. 1 mil minimum tin + babbitt
3. 1 mil minimum zinc + babbitt
4. All babbitt

The parts were flame sprayed by the same vendor who had cooperated during the engineering development effort. The spray gun was positioned a fixed distance from the capacitor, which was held in rotating chuck. The required coating thickness was approximately 12 mils. A metallographic specimen was prepared from each lot to examine the coatings. The approximate thicknesses of the flame sprayed coatings are summarized in Table 1.

TABLE 1. TERMINATION THICKNESS

| Lot | Sample Number | Undercoat, mils | Babbitt, mils |
|-----|---------------|-----------------|---------------|
| 1   | 1             | Al 2.5          | 10            |
| 2   | 13            | Tin 1.3         | 10            |
| 3   | 25            | Zinc 1.0        | 10            |
| 4   | 37            | None            | 12.5          |

Examination of the metallographic specimens indicated unevenness of the winding and variation of thickness of the flame sprayed coatings. The unevenness of the winding was attributed to the winding machine. This particular machine was designed for winding mica paper. The NASA machine designed for light gauge film was being modified and was not available. Lot 1 was rewound to obtain better aligned edges. The flame spraying was the same process as the original lot. The resistance measurements were lower and exhibited an average resistance of  $4.76 \text{ m}\Omega/\text{cm}^2$  compared to  $5.73 \text{ m}\Omega/\text{cm}^2$  for the original lot.

The results of the resistance measurements, given in Table 2, showed that the babbitt metal termination was the most consistent, with resistance measurements ranging from  $5.8$  to  $6.9 \text{ m}\Omega/\text{cm}^2$ . For the aluminum and babbitt combination, the resistance varied from  $5.6$  to  $11 \text{ m}\Omega/\text{cm}^2$ . For tin and babbitt the resistance varied from  $6.5$  to  $12.8 \text{ m}\Omega/\text{cm}^2$ , and for zinc and babbitt  $6.0$  to  $8.9 \text{ m}\Omega/\text{cm}^2$ .

The vendor who flame sprayed the above original lots closed its West Coast facility, which caused a schedule delay and a consequent increase in the technical effort. Three other local vendors were visited; two were felt to be promising. Several lots were flame sprayed by each vendor for evaluation and pulse testing.

TABLE 2. CHANGE IN TERMINATION RESISTANCE  
DUE TO PULSE TESTING AT 400 AMPERES/CM<sup>2</sup>

| Pulses  | S/N, mΩ |       |       |       |       |
|---------|---------|-------|-------|-------|-------|
|         | 51      | 52    | 53    | 54    | 55    |
| 0       | 4.7700  | 4.912 | 4.948 | 4.560 | 4.610 |
| 10      | 4.7200  | 5.040 | 5.048 | 4.548 | 4.590 |
| 30      | 4.8520  |       |       |       |       |
| 100     | 4.8900  | 5.060 | 5.040 | 4.604 | 5.604 |
| 300     | 4.8420  |       |       |       |       |
| 1,000   | 4.7980  | 5.054 | 5.072 | 4.662 | 4.618 |
| 3,000   | 4.8640  |       |       |       |       |
| 10,000  | 4.8460  | 5.042 | 5.096 | 4.696 | 4.652 |
| 30,000  | 4.8600  |       |       |       |       |
| 100,000 | 4.8280  | 5.072 | 5.040 | 4.643 | 4.698 |

The results of testing samples flame sprayed by the first new vendor are summarized in Table 3. The resistivities shown are the initial values. The quality of these parts is quite inferior to those made by the original vendor. The only apparent difference discerned in the processing was that the spray gun was closer to the work. Because of the poor quality, no further work was done with this vendor.

The tests amply demonstrated that low resistivity is required for long life and reliability. Again, the all babbitt terminations were superior.

#### TESTS AT HIGHER CURRENTS

Some additional pulse testing was conducted at higher currents of 600, 800 and 1000 A/cm<sup>2</sup> to determine the amount of current the terminations could conduct and the number of pulses. The testing was performed with the circuit shown in Figure 7. The current waveform at 400 amperes/cm<sup>2</sup> is shown in Figure 8. The pulsewidth was 50 μs with a repetition rate of 10 Hz.

The test results at the higher currents are presented in Table 4. Most of the terminations conducted 600 A/cm<sup>2</sup> adequately. Some failures occurred at 800 A/cm<sup>2</sup>. Only one part could conduct 1000 A/cm<sup>2</sup>.

TABLE 3. PULSE TESTS AT 400 A/CM<sup>2</sup>

| S/N | Termination  |                         | Number of Pulses |
|-----|--------------|-------------------------|------------------|
|     | Material     | Resistivity, m $\Omega$ |                  |
| 66  | Tin-Babbitt  | 6.96                    | 300              |
| 67  |              | 5.42                    | 30,250           |
| 68  |              | 7.46                    | 10               |
| 69  |              | 6.09                    | 1,000            |
| 70  |              | 15.45                   | 1                |
| 71  |              | 159.30                  | 1                |
| 72  | Zinc-Babbitt | 5.14                    | 100,000          |
| 73  |              | 60.35                   | 1                |
| 74  |              | 9.80                    | 1                |
| 75  |              | 14.74                   | 1                |
| 76  |              | 7.30                    | 30               |
| 77  | All-Babbitt  | 7.93                    | 300              |
| 78  |              | 8.70                    | 10               |
| 79  |              | 5.03                    | 100,000          |
| 80  |              | 5.16                    | 100,000          |
| 81  |              | 6.12                    | 100,000          |
| 82  |              | 6.11                    | 100,000          |
| 83  |              | 6.35                    | 100,000          |

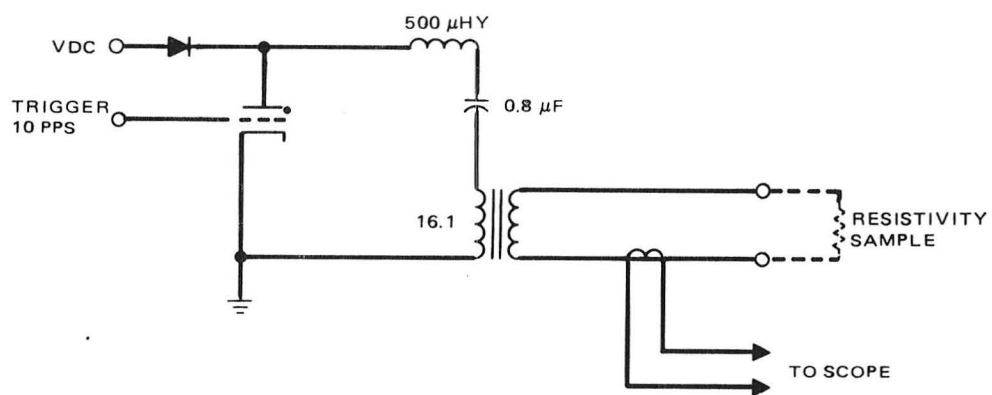
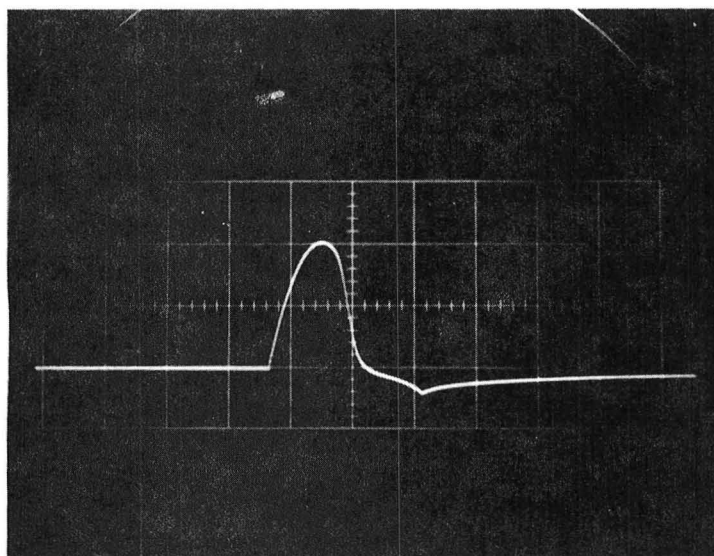


Figure 7. Pulse test circuit.



HORIZONTAL =  $50 \mu\text{s/cm}$   
 VERTICAL =  $200 \text{ A/cm}$

Figure 8. Current pulse waveshape.

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TABLE 4. HIGH CURRENT PULSE TESTS OF  
BABBITT TERMINATIONS

| S/N | Number of Pulses      |                       |                        |
|-----|-----------------------|-----------------------|------------------------|
|     | 600 A/cm <sup>2</sup> | 800 A/cm <sup>2</sup> | 1000 A/cm <sup>2</sup> |
| 79  | 36,000                | 36,000                | 18,800                 |
| 80  | 36,000                | 24,500                |                        |
| 81  | 1,356                 |                       |                        |
| 82  | 21,000                |                       |                        |
| 83  | 36,000                | 5,900                 |                        |

The results of testing samples flame sprayed by the second new vendor are summarized in Table 5. It is evident the quality of these terminations is somewhat better than the previous vendor. This vendor, therefore, was selected to flame spray the 260 capacitors for the test program.

TABLE 5. PULSE TESTS OF BABBITT TERMINATIONS

| S/N | Initial Resistivity, mΩ | Number of Pulses      |                       |                       |
|-----|-------------------------|-----------------------|-----------------------|-----------------------|
|     |                         | 400 A/cm <sup>2</sup> | 600 A/cm <sup>2</sup> | 800 A/cm <sup>2</sup> |
| 84  | 5.11                    | 100,000               | 36,000                | 29,000                |
| 87  | 5.38                    | 100,000               | 36,000                | 300                   |
| 89  | 12.3                    | 10                    |                       |                       |
| 90  | 5.22                    | 100,000               | 36,000                | 5,000                 |
| 92  | 4.41                    | 100,000               | 36,000                | 5,000                 |

Some typical data from the testing conducted at very high pulse currents is plotted in Figure 9. The curves from Figure 6 are used with the higher current data superimposed. The lower curve represents parts that did not exhibit any significant degradation after 100,000 pulses at



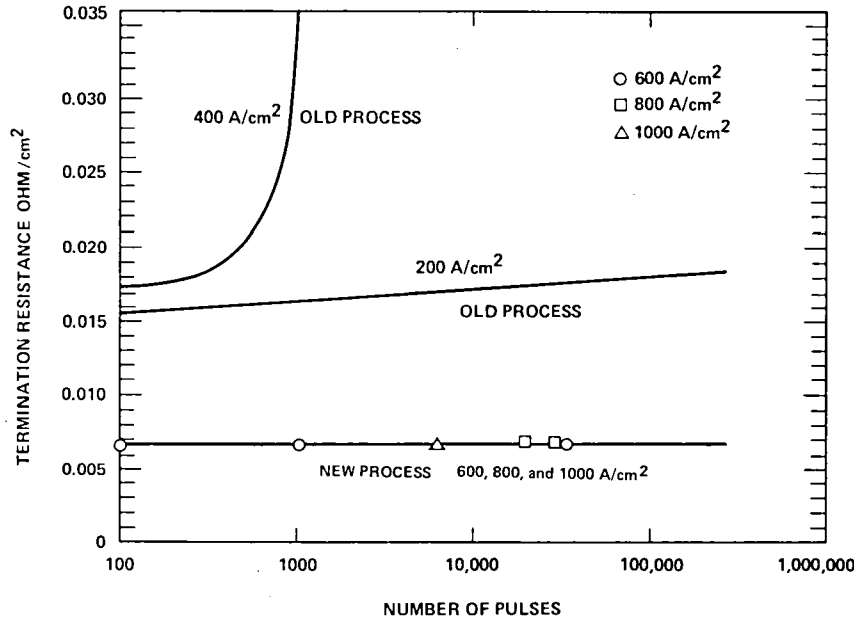


Figure 9. Change in termination resistance.

400 A/cm<sup>2</sup>. The parts tested at the higher currents also did not show any degradation. If the initial resistivity is low enough the terminations can conduct currents of 400 A/cm<sup>2</sup> reliably for more than 100,000 pulses. At larger currents the lifetime was reduced but was still substantial.

## DISCUSSION OF RESULTS

Resistivity samples tested at 200 and 400 A/cm<sup>2</sup> demonstrated that improved terminations could be achieved by controlling the metal spraying process. In particular, the distance from the spray gun to the work was fixed and the spraying time was predetermined and closely controlled.

Many two-metal terminations were compared. The results showed that the all-babbitt metal terminations provided the most consistent resistivity. None of the two-metal combinations appeared to be better than babbitt alone.

The tests amply demonstrated that low termination resistance is essential for long life and reliability. Good terminations were capable of reliably conducting currents of 400 A/cm<sup>2</sup> for more than 10<sup>5</sup> cycles. At larger currents of 600 and 800 A/cm<sup>2</sup>, the lifetime was reduced but was still substantial.



### III. CAPACITOR FABRICATION

#### POLYVINYLIDENE FLUORIDE FILM PROPERTIES

This material, primarily used for coverings of greenhouses, is attractive as a capacitor dielectric because of its high dielectric constant, shown in Figure 10. The stability of this property with temperature and frequency is remarkable, given the highly polar nature of the original molecules needed to produce it.

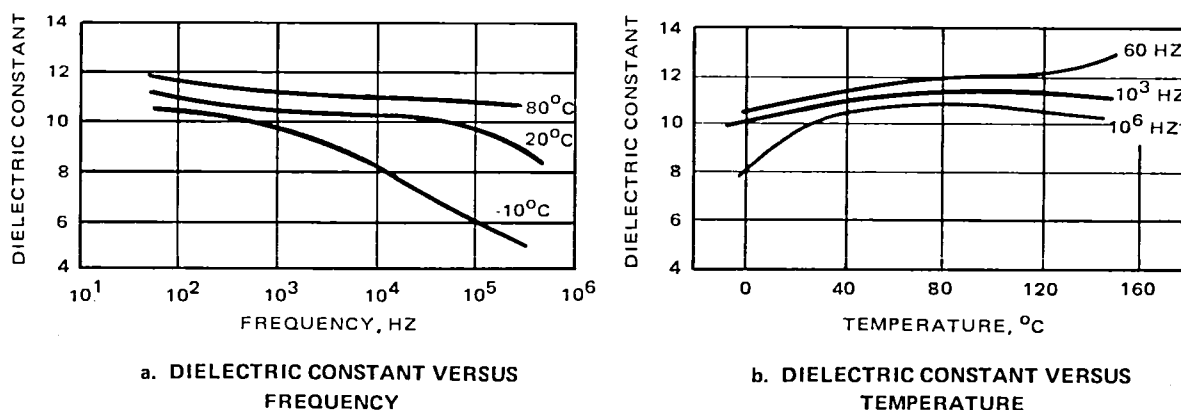


Figure 10. Dielectric constant of KF polyvinylidene fluoride.

These data were taken on polyvinylidene fluoride produced by Kureha Chemical Industry of Japan under the name KF polymer and distributed in this country by Kreha Corporation. The KF polymer is an extruded biaxially oriented film; the biaxial orientation is achieved by stretching the film more than 50 percent in each direction after extrusion. This stretching and the molecular chain orientation it produces appear to be responsible for some of the unusual electrical properties of this material.

The large dielectric constant immediately implies a lower electric field to meet the required energy density compared to materials of lower dielectric constant. This film is available in 6.0  $\mu\text{m}$  (0.24 mil) thickness and has an energy density at 500 VDC of 0.188 J/g (84.6 J/lb) and required electric field of  $8.33 \times 10^5$  V/cm (2083 V/mil).

The dissipation factor of PVF2 is quite large and variable with temperature and frequency as shown in Figure 11.

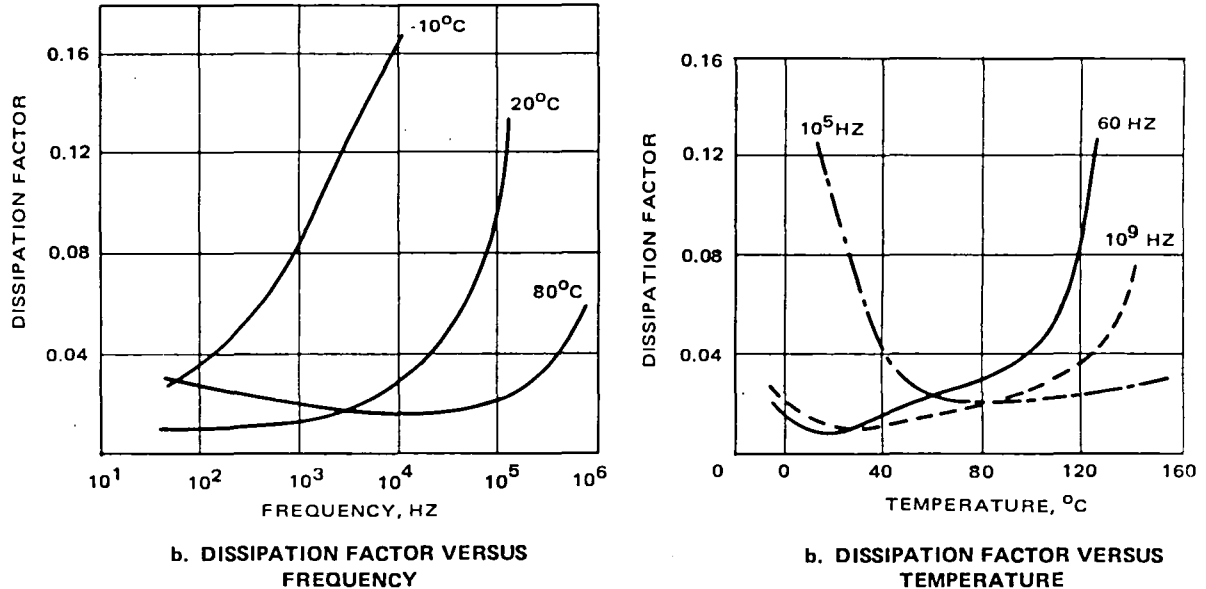


Figure 11. Dissipation factor of KF polyvinylidene fluoride.

The KF film is a chemical relative of polyvinylidene chloride — the material used for Saran wrap. The KF polymer inherits the family tendency toward limpness; in addition, it exhibits enhanced static electricity problems during winding, because of the combination of high dielectric constant and high volume resistivity.

The service temperature of this material is about  $160^\circ\text{C}$ , on the basis of insulation resistance, see Figure 12, and other measurements. In the form for this application, use at high temperatures is governed by the irreversable shrinkage which if unconstrained reaches 2 percent at  $125^\circ\text{C}$ .

#### CAPACITOR CONSTRUCTION

The designs and methods described in this section were used to build the components that were tested later in the program.

#### Design

Two sizes of capacitors,  $0.1\text{ }\mu\text{F}$  and  $2\text{ }\mu\text{F}$ , were fabricated for testing. The design data for the  $0.1\text{ }\mu\text{F}$  capacitor is summarized in Table 6. The design for the  $2\text{ }\mu\text{F}$  capacitor is summarized in Table 7. Both types used Kureha KF polymer which was metallized by Schweitzer Division, Kimberly-Clark Corp.

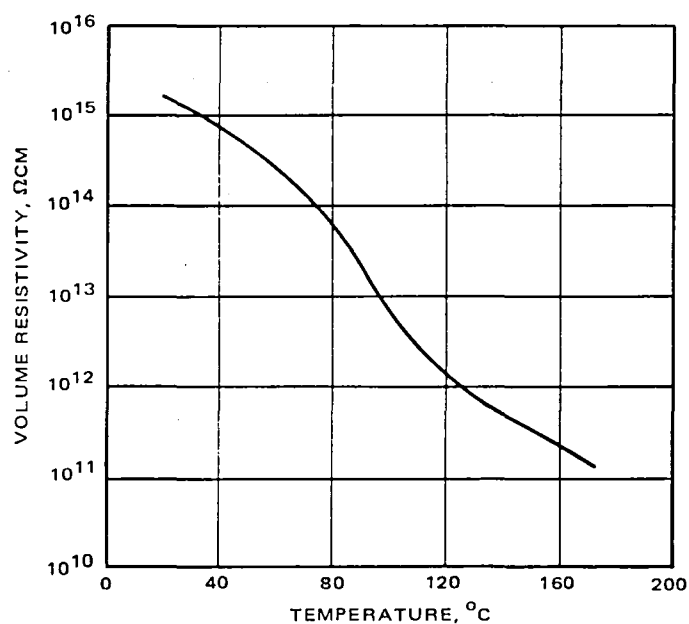


Figure 12. Volume resistivity of KF polyvinylidene fluoride.

TABLE 6. DESIGN DATA FOR 0.1  $\mu$ F CAPACITORS

|                     |  |                        |
|---------------------|--|------------------------|
| 1. <u>Capacitor</u> |  |                        |
| Capacitance         |  | 0.1 $\mu$ F            |
| Voltage             |  | 500 VDC                |
| Outside Diameter    |  | 0.53 cm (0.210 in)     |
| Length              |  | 0.76 cm (0.300 in)     |
| 2. <u>Film</u>      |  |                        |
| Dielectric          |  | 6 $\mu$ m PVF2         |
| Width               |  | 0.64 cm (0.25 in)      |
| Metallization       |  | Aluminum               |
| Resistivity         |  | 1 - 2 $\Omega/\square$ |
| Margin              |  | 0.157 cm (0.062 in)    |
| 3. <u>Winding</u>   |  |                        |
| Length              |  | 125 cm (49 in)         |
| Offset              |  | 0.079 cm (0.031 in)    |
| Spindle Diameter    |  | 0.20 cm (0.080 in)     |

TABLE 7. DESIGN DATA FOR 2  $\mu$ F CAPACITORS

|                     |  |                        |
|---------------------|--|------------------------|
| 1. <u>Capacitor</u> |  |                        |
| Capacitance         |  | 2 $\mu$ F              |
| Voltage             |  | 500 VDC                |
| Outside Diameter    |  | 0.89 cm (0.350 in)     |
| Length              |  | 2.62 cm (1.030 in)     |
| 2. <u>Film</u>      |  |                        |
| Dielectric          |  | 6 $\mu$ m PVF2         |
| Width               |  | 2.38 cm (0.938 in)     |
| Metallization       |  | Aluminum               |
| Resistivity         |  | 1 - 2 $\Omega/\square$ |
| Margin              |  | 0.157 cm (0.062 in)    |
| 3. <u>Winding</u>   |  |                        |
| Length              |  | 376 cm (148 in)        |
| Offset              |  | 0.079 cm (0.031 in)    |
| Spindle Diameter    |  | 0.20 cm (0.080 in)     |

Metallized capacitor film is commonly supplied with either 0.32 cm (0.125 inch) margins or 0.16 cm (0.063 inch) margins. To establish the margin design width, the breakdown voltage was determined for various widths. Small pieces of PVF2 film were metallized with margins varying from 0.042 to 0.300 inch. The breakdown voltage was measured in air and in oil. A special test fixture was used that simulated capacitor conditions.

A plot of the test data for air is shown in Figure 13. The breakdown voltage varied from 2 to 4.3 kV. The maximum was 52 V/mil. In oil, the breakdown voltages and stress were higher by a factor of 4. It was concluded that the smaller margins of 0.10 to 0.23 cm (0.040 to 0.090 inch) were sufficient.

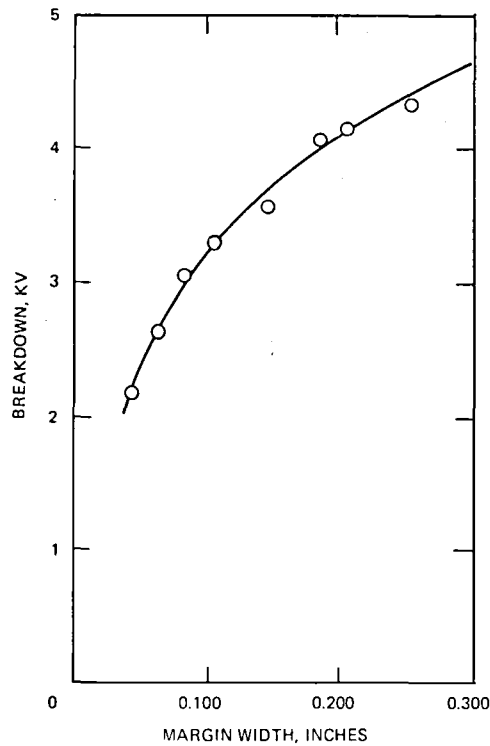


Figure 13. Breakdown voltage for metallized PVF2 versus margin width, in air.

### Capacitor Winding

A small capacitor winder that had been specifically designed and built to wind developmental capacitors from narrow widths of thin gauge capacitor films was used for winding both sizes of capacitors for the test program. This machine uses AC torque motor tension control to provide constant dynamically controlled low tension in the film during the winding operation. Since the films are very delicate, low tension is required to avoid film wrinkling, stretching, or rupture. The tension must also be constant for all speeds of the winding spindle to yield good quality, uniformly wound components. The low tension requirement dictates that the tensioning system presents a low frictional torque on the film bobbin shafts. The capacitor film bobbins are mounted directly on the shafts of the torque motors. Inertia and friction of the tension sensing arms also have been minimized. The tension sensing arms are equipped with easily adjustable

pneumatic dampers that prevent oscillation in the tension control system when the winding operation is started or when the winding speed is changed. Film tension is approximately 3 to 8 kg/mm<sup>2</sup>. The film bobbins can be positioned easily along the winding mandrel by axial adjustment of the torque motor mounts. This machine was designed to have a short span of film between the bobbins and the mandrel to minimize axial run out of the film while a capacitor is being wound. The winder is shown in Figures 14 and 15.

The capacitors developed previously were wound on cores of 1/8 inch teflon tubing. The film was bonded directly to the core with Loctite 404 or Eastman 910 adhesive. When the desired length of film was wound, the capacitor was completed by cutting the second film and winding over the cut end with two or three turns of the first film. Then the first film was cut and its cut end cemented to the capacitor pad. This construction is shown in Figure 16.

The metallization was etched away electrically to form the end margins on the second sheet of the capacitor. The film was grounded with a large area electrode, about 1/2 inch<sup>2</sup>, and then sweeping a needle electrode held at 70 VDC over the film where the metallization was to be removed.

Many methods are being used to start the winding of metallized film capacitors. These include special shaped bobbins, taping the film to the bobbin, and manually removing the metallization at the beginning of the film. These schemes all have certain shortcomings, including being proprietary or not being suitable for production.

A suitable start technique is needed to wind wrinkle-free capacitors; thin gauge films are especially difficult to start satisfactorily. Many different techniques were investigated.

An excellent technique developed for this program, shown schematically in Figure 17, consisted of using a short strip of film to form a core and anchor the metallized film. Both teflon and PVF2 were evaluated with the rod and adhesive start. The test results are shown in Table 8. It is evident that both the teflon and PVF2 are considerably better than the rod and adhesive. Since the teflon leader was thicker than the PVF2, a thicker oil film resulted that might have caused the teflon design to break down at a lower voltage than the PVF2.



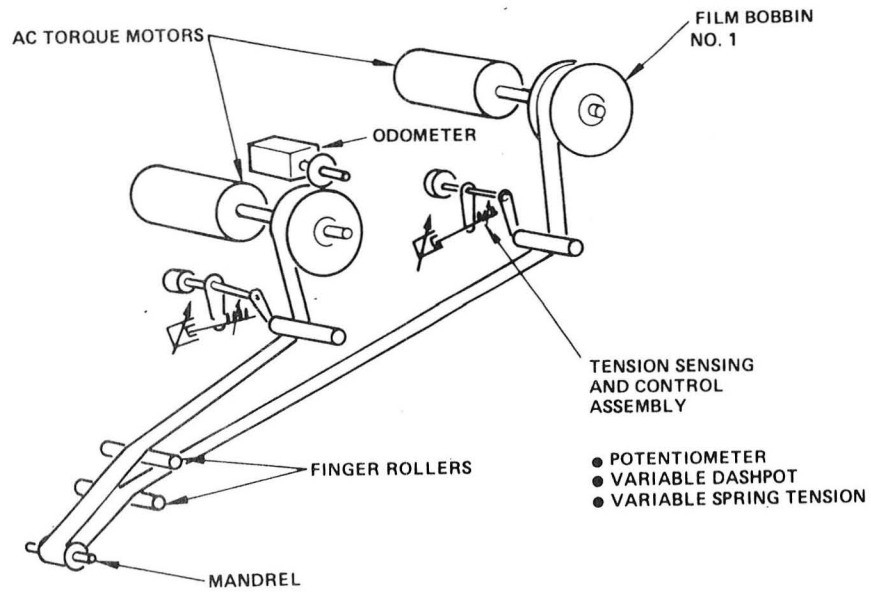
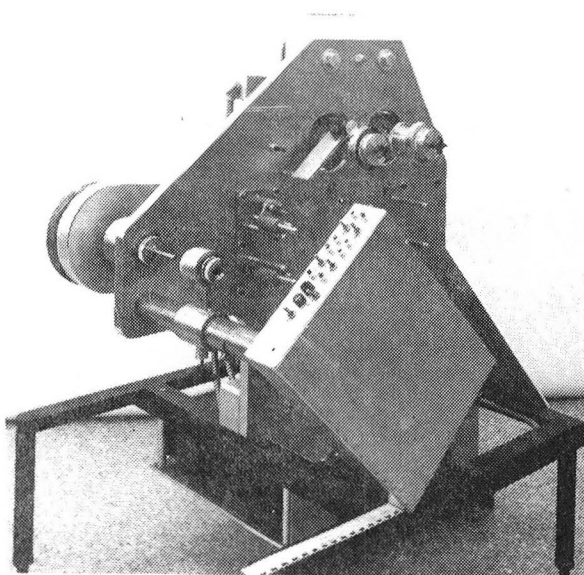


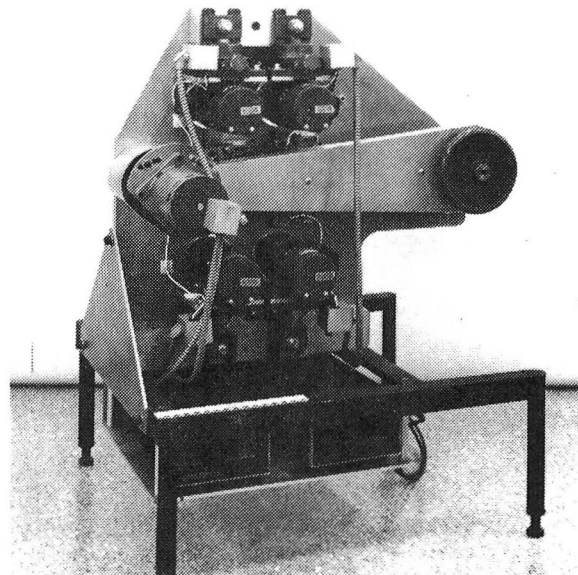
Figure 14. Capacitor winder schematic.

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a. Front view

4R-50071



b. Rear view

4R-50069

Figure 15. Capacitor winder.

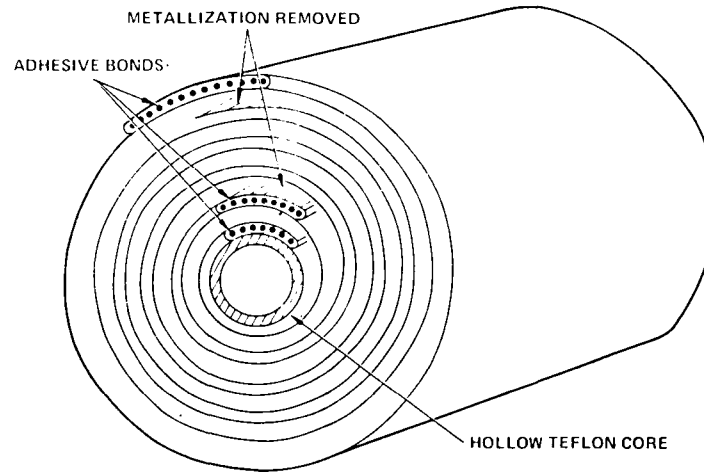


Figure 16. Construction of cylindrical capacitor.

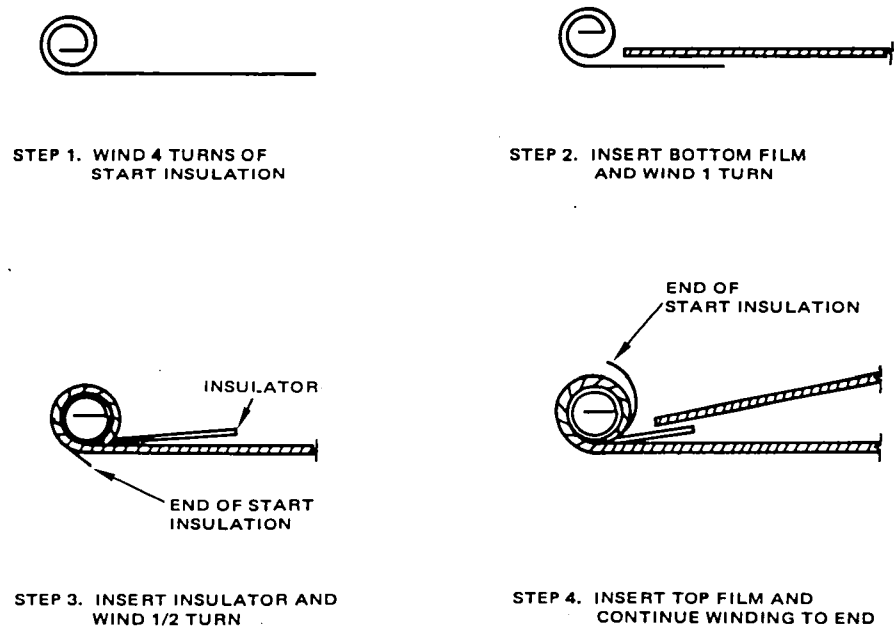


Figure 17. Improved winding — start technique.

TABLE 8. COMPARISON OF WINDING-START METHODS. CAPACITORS  
IMPREGNATED WITH DIOCTYL PHTHALATE

| Start Method        | S/N | $\mu\text{F}$ | DF   | Bkdn, V | Comments                                 |
|---------------------|-----|---------------|------|---------|--|
| Rod and<br>Adhesive | 1   | 2.94          | 9.1  | 700     | Breakdown at finish                      |
|                     | 2   | 2.89          | 2.15 | 600     | Breakdown 12 inches<br>from start        |
|                     | 3   | 3.0           | 15.8 | 300     | Breakdown 6 inches<br>from start         |
|                     | 4   | 2.89          | 2.35 | 700     | Breakdown on edge<br>at middle           |
|                     | 5   | 2.91          | 2.08 | 600     | Breakdown 1/3 from<br>start              |
|                     |     |               |      | av 580  |  |
| Teflon Leader       | 1   | 2.86          | 2.7  | >1000   | Breakdown at start<br>Breakdown at start |
|                     | 2   | 2.90          | 3.1  | >1000   |  |
|                     | 3   | 2.77          | 11.0 | 990     |  |
|                     | 4   | 2.83          | 2.65 | 800     |  |
|                     | 5   | 2.77          | 2.90 | >1000   |  |
|                     |     |               |      | av 958  |  |
| PVF2 Leader         | 1   | 1.940         | 1.90 | 500     |  |
|                     | 2   | 1.989         | 1.85 | >1000   |  |
|                     | 6   | 1.882         | 1.60 | >1000   |  |
|                     | 7   | 1.888         | 1.83 | >1000   |  |
|                     | 8   | 1.884         | 1.38 | >1000   |  |

The new technique has the following advantages:

1. No tooling is required.
2. No special bobbins are required.
3. It is suitable for production.
4. A cylindrical core without lumps results.

### Terminations

All terminations were made, as discussed above, under closely controlled conditions in which the gun-to-capacitor distance was fixed and the spraying time was pre-determined. This improved method was combined with the selection of babbitt metal, close control of the margin and offset, and winding with the metallized sides of the capacitor film on the outside to secure superior terminations.

After flame spraying, all sections were cleared at 600 VDC. The energy was supplied from a charged capacitor.

### Case Design and Assembly

A hermetically sealed capacitor case was designed, for each size capacitor, similar to those used for commercial and MIL type capacitors. Both designs utilized readily available thin walled tubing and electrical feedthroughs. A cross-section view showing the construction is shown Figure 18. The case cylinder was brass tubing, tin plated. The wall thickness was 0.018 cm (7 mils). The feedthroughs were Kovar-glass. For the electrical connection, the wire lead was soft soldered to the flame sprayed babbitt. To make the hermetic seal, the feedthroughs were soft soldered to the case and lead. After impregnation, the remaining lead was soldered to the feedthrough to make the final seal.

The processing to assemble the capacitor is important in achieving reliable performance. The design of the above case is consistent with these stringent requirements. The construction is entirely of metal and glass. The case may be chemically cleaned and vacuum baked out at elevated temperatures. The Kovar and glass are compatible with normal impregnants.

### Impregnation

The impregnation processing followed procedures previously developed for high energy density capacitors. The capacitors were dried and

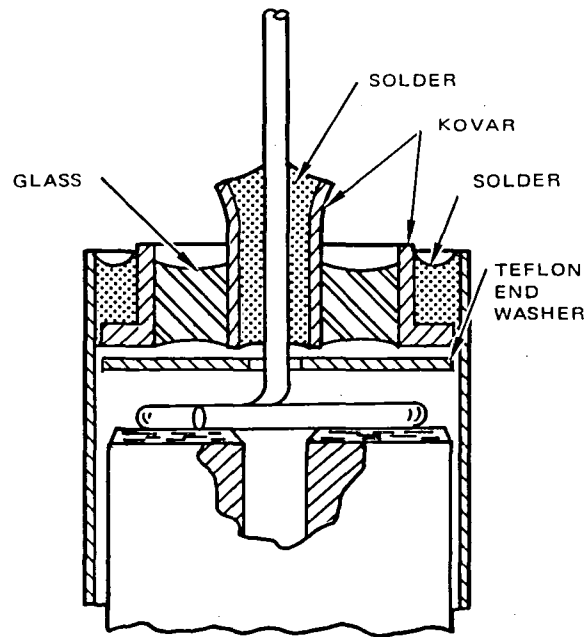


Figure 18. Capacitor case design (one end).

impregnated as a single step. The impregnant and the capacitor must be completely dry. The impregnant must be of as high a resistivity as possible and completely free from particulate contamination.

A standard type fluid impregnator manufactured by Red Point was modified to achieve these results. It consisted of a main chamber, a side loader for fluid and a very high capacity pump. Both the main chamber and side loader have provisions for heating.

On the basis of initial experiments, the only practical way to use this equipment for high resistivity impregnation was to continuously filter and purify the oil under vacuum in the machine. When the capacitors were ready for impregnation, the fluid would be diverted from its cycle loop and poured into the capacitors. In this way, the purest possible fluid would be obtained for the capacitors.

The modified filter loop is shown in Figure 19. The entire circuit, as well as the chamber (not shown) in which the capacitors are dried, is maintained under vacuum by the large process pump attached to the machine.

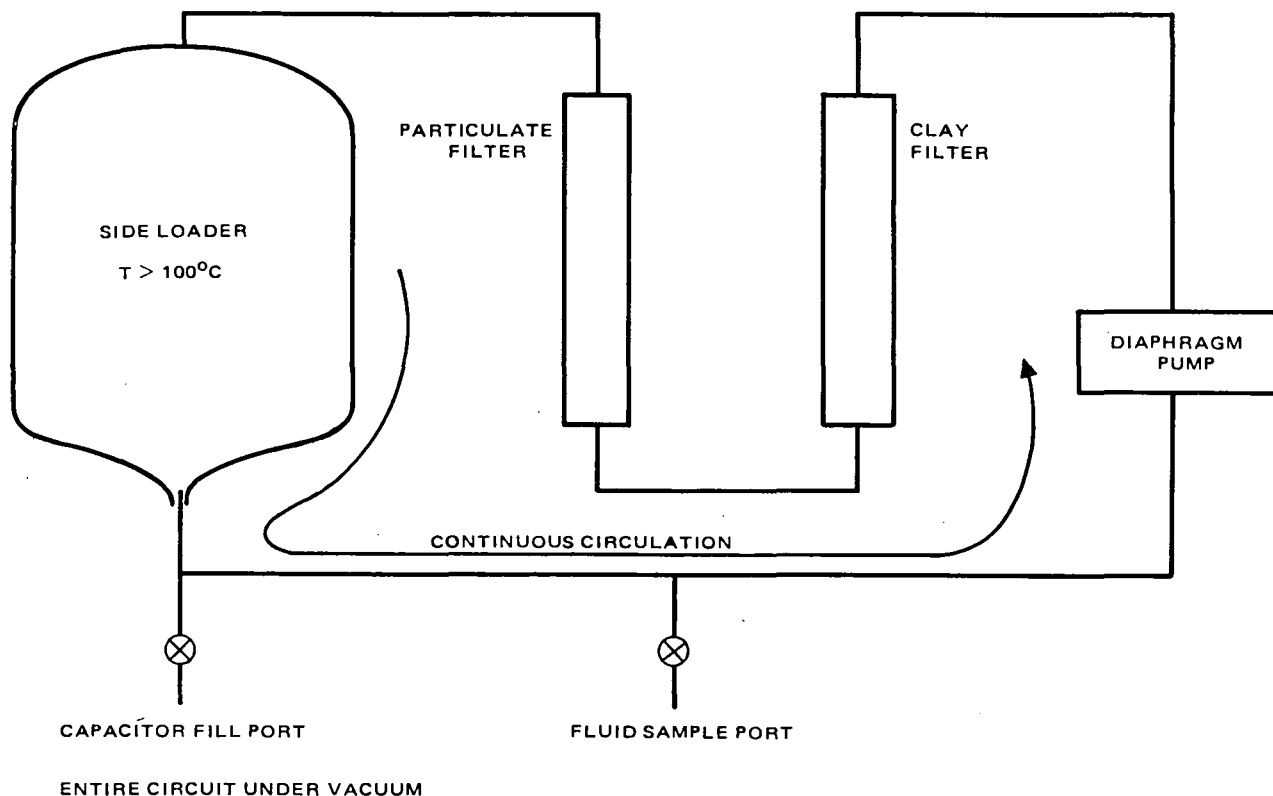


Figure 19. Fluid process cycle.

To minimize the chance of introducing metal particles into the fluid, the added lines and recirculating pump have no exposed metal parts.

The impregnation procedure is straightforward. The side loader was filled with dioctyl phthalate (DOP) fluid, and the capacitors to be filled were placed in the main chamber. Vacuum was obtained in both areas, and the fluid was heated, filtered, and degassed. The fluid was sampled at the end of this cycle to ascertain that it was sufficiently pure. Typical values obtained were resistivity  $5 \times 10^{12} \Omega\text{-cm}$  and water content 14 ppm. The capacitors were dried at  $85^{\circ}\text{C}$  for 24 hours. At the end of the drying period, the capacitors were slowly filled over a 2-hour period with DOP. After filling, they were left in vacuum at  $85^{\circ}\text{C}$  for 24 hours and then slowly cooled to room temperature. The capacitors were sealed immediately after they were removed from the vacuum system.

## DISCUSSION OF RESULTS

Polyvinylidene fluoride is attractive as a capacitor dielectric because of its high dielectric constant. The large dielectric constant implies a lower electric field to meet the required energy density compared to materials of lower dielectric constant. However, it is usually not practical to utilize the high dielectric constant of PVF2, since the dielectric constant of most impregnating fluids is low.

The dissipation factor (DF) is quite large and increases with increasing temperature. For AC applications this large dissipation factor is of decisive importance.

PVF2 film tends to be limp and in addition exhibits enhanced static electricity problems during winding. As a result, especially in the 6  $\mu$ m gauge, it is difficult to handle during winding and slitting operations. Control of the humidity at about 50 percent and careful winding were helpful in overcoming these problems.

The capacitor designs used for this program were consistent with previous designs developed for NASA.

The breakdown voltage was determined for various margins to establish the margin design. The breakdown voltage varied from 2 to 4.3 kV in air. It increased by a factor of 4 in oil. The results indicated that smaller margins of 0.10 to 0.23 cm were sufficient.

A number of start techniques were investigated. A remarkably good technique, developed for this program, consisted of using a short strip of PVF2 film to form a core and anchor the metallized film. The test results showed that this technique was superior to a previous design that had been adequate.

All terminations were made under closely controlled conditions to ensure superior terminations. Hermetically sealed cases were designed for each size capacitor that utilized commercial thin walled tubing and Kovar-glass feedthroughs. Construction was entirely of metal and glass.

The impregnation processing followed procedures developed for high energy density capacitors. Dioctyl phthalate fluid was used and continuously filtered and purified under vacuum. It was monitored for resistivity, water content, and particulate matter. The capacitors were carefully dried before impregnation.



#### IV. TEST PROGRAM AND TECHNIQUES

Under two previous NASA contracts, 2  $\mu$ F 500 VDC ultra lightweight capacitors were developed. A 2500-hour life test was performed at room temperature. Testing was limited at extreme ambient and operational conditions. To ascertain the full operating capability of these capacitors, more extensive testing was needed. The present contract fulfilled these shortcomings by operating the capacitors under extreme environmental and operational conditions to determine their operational limits. Part of the tests and test procedures used came from MIL-C-39022C and MIL-STD-202E.

##### AUTOMATED TEST SYSTEM

The capacitor characteristics, test data, and data analysis were obtained with an automated computer-controlled system. This system is shown in Figure 20. The controller, the HP 9845 desk-top computer with a CRT readout is shown at the lower center, and a printer is shown on the left. A Statham oven and temperature controller are shown in the center. A digital bridge is to the right of the computer. A scanner is shown in the



Figure 20. HP 9845 computer system.

rack at the right. A block diagram of the complete system is shown in Figure 21.

This very powerful computer with its peripheral equipment has the following features:

1. Full automation
2. On-line data reduction
3. Precise low level measurements ( $1\mu$  volt sensitivity)
4. High speed program/data storage (tape disk) (0.5 megabyte)
5. Access priority interrupt
6. True RMS AC, average or sampled
7. DC and ohms measurements to 7-1/2 digits
8. 1 MHz bandwidth
9. High equivalent common mode rejection
10. Thermal printer and color plotter

These features can be used to implement mathematical modeling, analysis of circuit designs, control of tests, and versatile display of analyzed data through expanded graphics capability. Together with the Extended Basic Language, this system affords personnel the opportunity to exercise unusual versatility in problem solving and approaches to more effective data presentation.

The accuracy and frequency ranges of the instruments used for measuring capacitors are presented in Figure 22.

The peripheral equipment used is detailed below:

1. HP 3455A DDM. Provides the capability of DC measurement rates up to 19 channels per second with  $1\mu\text{V}$  resolution. With its excellent noise rejection ( $>140\text{ dB}$ ) and very low thermal uncertainty, the system is particularly suited for accurate repeatable low level measurements. AC measurements can be made up to 1 MHz with the AC true RMS converter.
2. Guideline 9577. A 7-1/2 digit DMM that provides accuracy and resolution of  $<0.1\text{ ppm}$ .

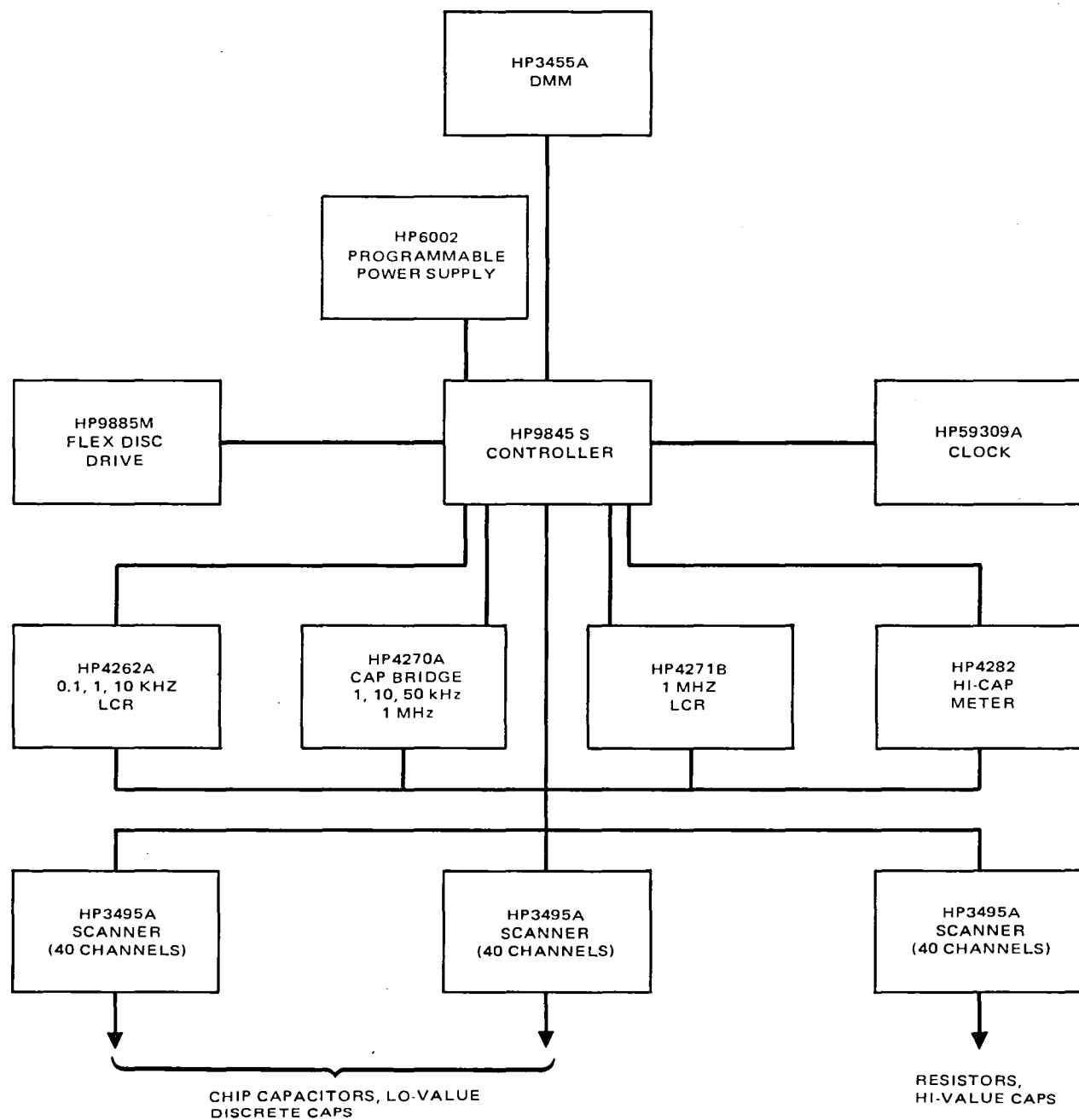


Figure 21. HP9845 computer system block diagram.

| INSTRUMENT                           | FREQUENCY |       |       |       | Q OR $\frac{1}{D}$ |                 | C IN FARADS, L IN HENRIES OR R IN OHMS |                  |                  |                  |                 |                 |                 | BASIC ACCURACY |    |     |
|--------------------------------------|-----------|-------|-------|-------|--------------------|-----------------|--|------------------|------------------|------------------|-----------------|-----------------|-----------------|----------------|----|-----|
|                                      | 1 Hz      | 1 kHz | 1 MHz | 1 GHz | 10 <sup>0</sup>    | 10 <sup>3</sup> | 10 <sup>-12</sup>                      | 10 <sup>-9</sup> | 10 <sup>-6</sup> | 10 <sup>-3</sup> | 10 <sup>0</sup> | 10 <sup>3</sup> | 10 <sup>6</sup> | 0.1%           | 1% | 10% |
| DIGITAL LCR METER 4262A              |           | •     | •     |       |                    |                 |  |                  |                  |                  |                 |                 |                 |                | •  |     |
| AUTO C-BRIDGE 4270A                  |           | •     | •     | •     |                    |                 |  |                  |                  |                  |                 |                 |                 |                | •  |     |
| 1 MHz LCR METER 4271B                |           |       |       | •     |                    |                 |  |                  |                  |                  |                 |                 |                 |                | •  |     |
| DIGITAL HIGH CAPACITANCE METER 4282A | •         | •     |       |       |                    |                 |  |                  |                  |                  |                 |                 |                 |                | •  |     |
| MULTI-FREQUENCY LCR METER 4275A      |           | •     | •     | •     |                    |                 |  |                  |                  |                  |                 |                 |                 |                |    |     |

Figure 22. Test equipment for capacitor measurements.

3. HP 3495A Scanners. Switches analog input signals to an appropriate measuring device. These can also control external devices with relay actuator closures. Low thermal relay assemblies are provided for DC measurements and transducer sensing.
4. HP 98035A Real Time Clock. Has a 30 ppm accuracy, provides real-time information, interrupts at specific times, and has an optional external trigger cable that can be used to output pulses to external devices.
5. HP 9885M Flexible Disk Drive. Provides 1/2 megabyte storage and allows for consistent organized data and program storage.
6. HP 59501A Power Supply Programmer. Provides a DC voltage control through any HP power supply via the HP-IB Interface Bus.
7. HP 9862A Four-Color Plotter. Produces high quality, multi-color graphic plots up to 280 x 432 mm chart size.

For test, the capacitors were mounted on circuit boards that, for convenience, held 40 capacitors. The boards were fabricated from aluminum sheet with standoff insulators for the capacitors, as shown in Figure 23. The boards were evaluated by comparing measurements made manually and

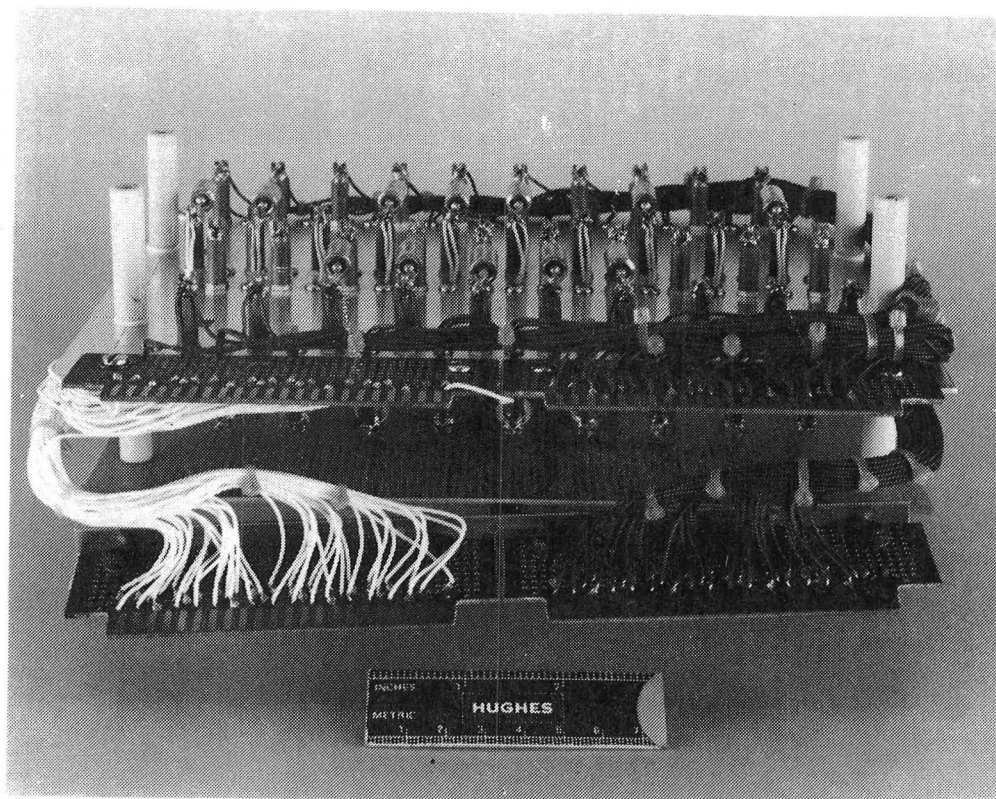


Figure 23. Test fixtures.

automatically off the board and on the board. Tests to measure the leakage at 125°C were also made.

#### CORONA TEST EQUIPMENT

A highly modified Biddle corona test set, shown in Figure 24, was the basic apparatus used. It consisted of AC and DC power supplies to stress the component under test, a power separation filter to isolate the corona pulses from the applied loads, and an instrumentation channel to measure the pulses. This channel had a wideband detector, a 30 to 300 kHz pulse amplifier, and an oscilloscope. The apparatus also included a pulse generator used to calibrate the instrument channel with a test component in place.

Power for AC tests was supplied by a 60 kV 60 Hz corona-free transformer. For DC measurements, a 0-40 kV supply that had extremely low output noise was used. AC and DC voltages can also be applied simultaneously to the specimen to simulate actual spacecraft power supply operation.

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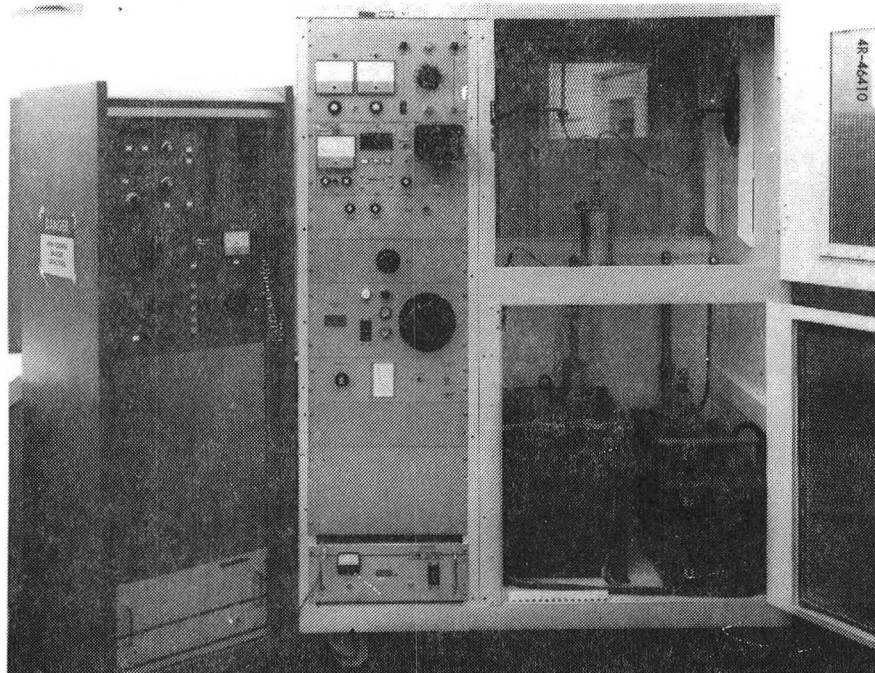


Figure 24. Biddle corona test equipment. (Upper test chamber shows typical test set-up for measuring AC corona in 1  $\mu$ F, 10 kV oil-filled capacitor)

A large amount of effort was expended to decrease the power supply output noise, the limiting factor in detection sensitivity. The Biddle was rewired to eliminate numerous noise-enhancing ground loops. Line regulation and elaborate filtering were used to provide quiet input power. These filters and regulators occupy the lower half of the left rack in Figure 24.

To make quantitative measurements, Hughes developed a high sensitivity digital corona pulse counter to measure the intensity of the corona. This counter in its latest form is shown in Figure 25.

The counter was designed to count pulses of different picocoulomb (pC) levels from 1 to 1000 pC and segregate them according to amplitude. Eight channels can be set and calibrated simultaneously to count pulses of different amplitudes. A summation of the counts weighed according to their pC level provides a quantitative measure of the total charge transfer in the corona discharge, i.e., the corona intensity.

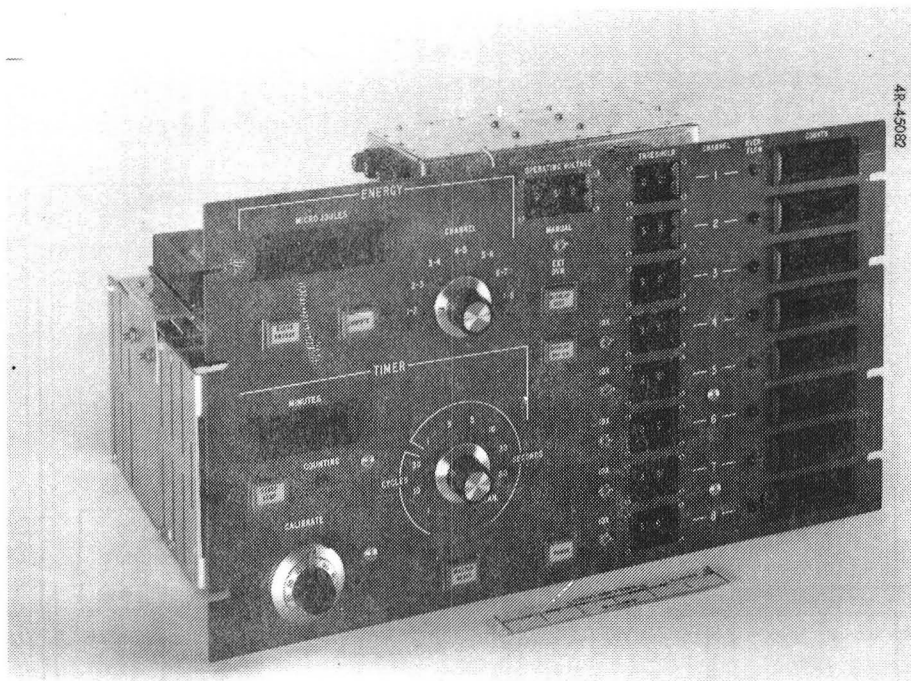


Figure 25. Hughes developed corona counter.

## TEST PROGRAM REQUIREMENTS

The test program comprised the following tasks:

1. Capacitor Characteristics
2. Low Temperature
3. Life Test
4. Thermal Cycling
5. Vibration.

The requirements of the test program were to test and operate 260 capacitors under extreme operational conditions and to electrically characterize them. These characterizations included capacitance and dissipation factors at frequencies from 10 Hz to 100 Hz; also, capacitance, dissipation factor and insulation resistance at elevated temperatures and various frequencies. In addition, the capacitors were tested for the existence of corona. A flow chart of the complete test program is given in Figure 26.

The techniques and results of the measurements are discussed in the following chapters.

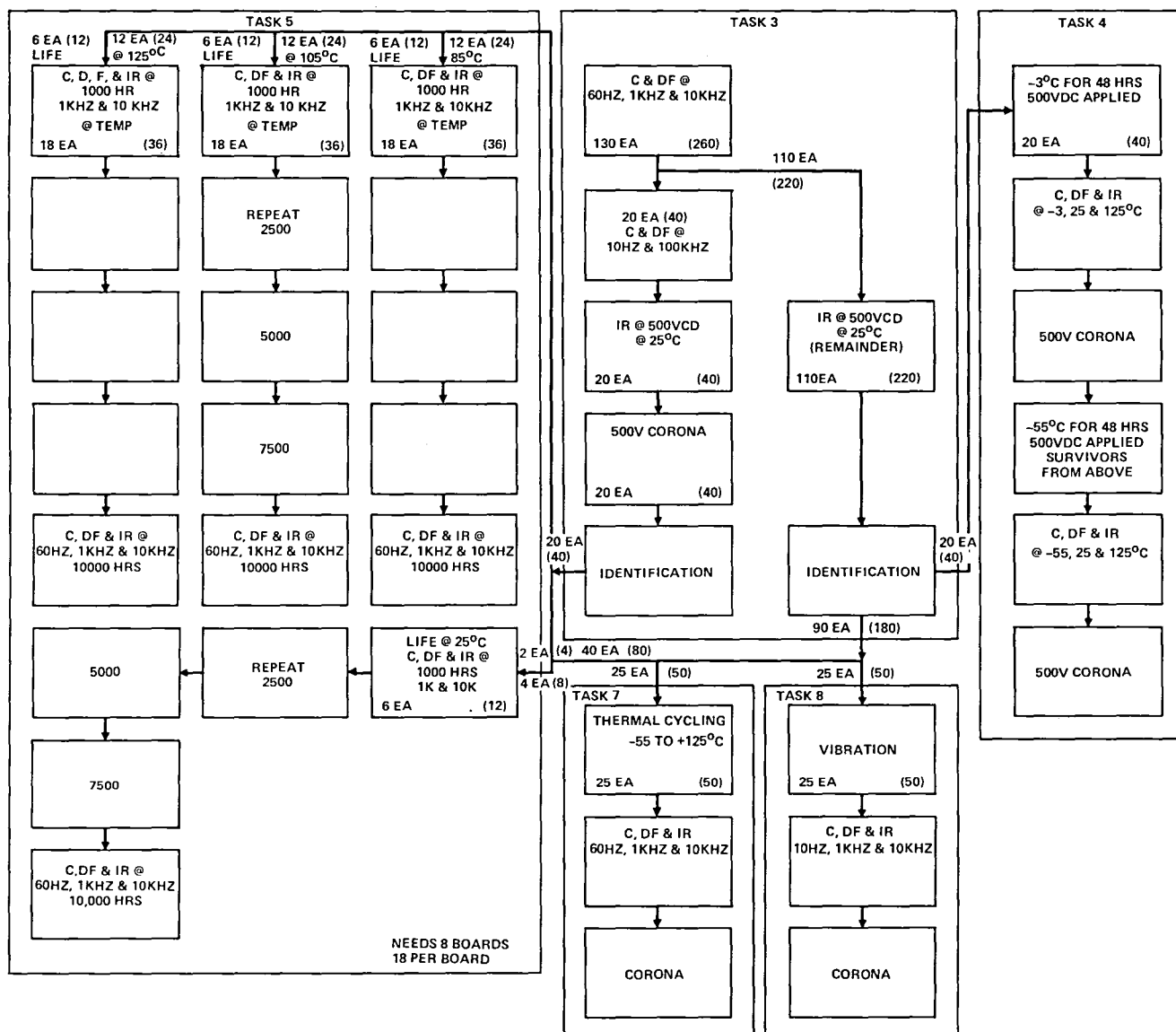


Figure 26. Test program flow chart.



## V. CAPACITOR CHARACTERISTICS

The requirement of this set of tasks was to electrically characterize 260 capacitors fabricated for the environmental tests and life test. These characterizations included capacitance and dissipation factor (DF) over a range of frequencies, DC resistance, and corona.

The detailed measurement requirements of Task 3 are summarized below:

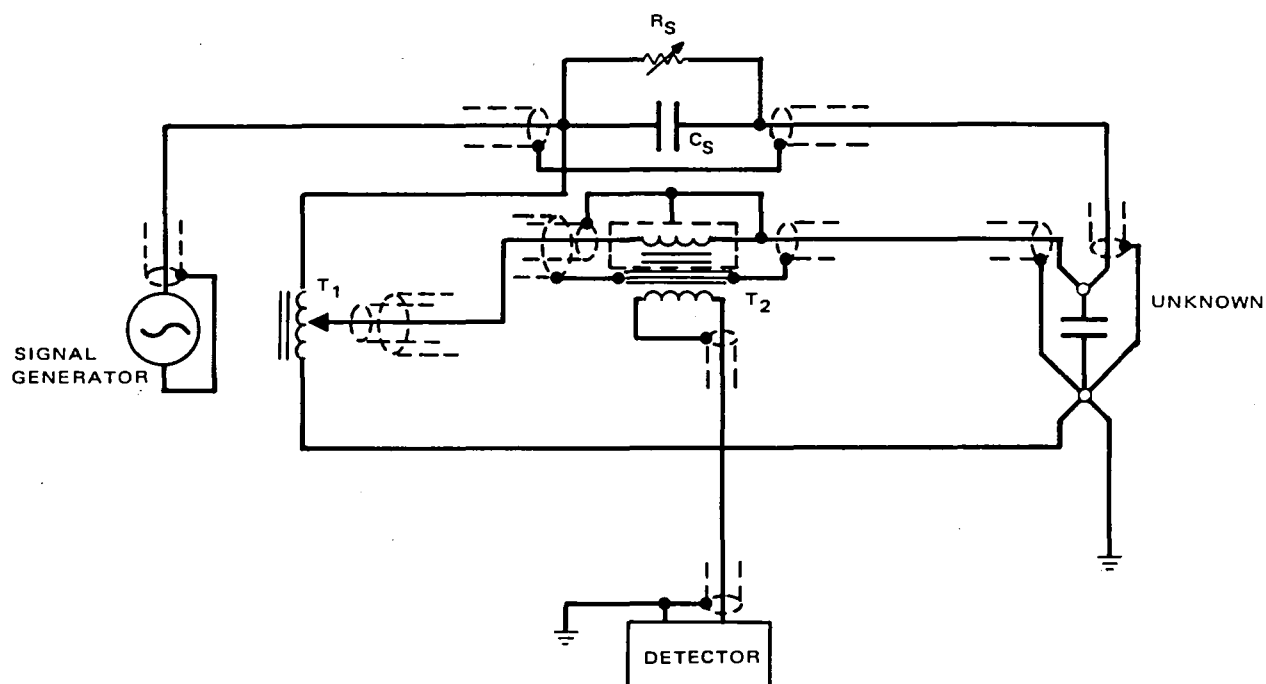
1. Capacitance versus Frequency at five frequencies from 10 Hz to 100 kHz
2. Dissipation Factor versus Frequency at five frequencies from 10 Hz to 100 kHz
3. Direct Current Resistance at 500 VDC
4. Corona Measurement at 500 VDC and 40 VAC

### CAPACITANCE AND DF VERSUS FREQUENCY

The capacitors were all measured for capacitance and DF at 60 Hz, 1 kHz and 10 kHz at 25°C. These data were obtained using the HP 9845 Computer System. The Hp 4262 Digital LCR Meter was used for measurement.

The measurements at 100 kHz could not be obtained with standard commercial test equipment. A transformer ratio arm bridge was assembled for these tests. The bridge circuit, shown in Figure 27, was configured to minimize errors due to lead wire inductance and resistance. In addition, equations were developed to correct for the non-ideal properties of the standard decade resistor  $R_p$  and the standard capacitor  $C_s$  of the bridge.

The equivalent high frequency circuit of  $R_p$  and  $C_s$  in parallel is shown in Figure 28. This circuit includes the inductance  $L_r$  and the capacitance  $C_t$  of the standard decade resistor plus the inductance  $L_s$  and the equivalent resistance  $R_s$  of the standard capacitor. The values of these corrective impedances were obtained from standards laboratory measurements and the manufacturer's technical data.



$T_1$ : DYTRONICS RT-501, RATIO TRANSFORMER  
 $T_2$ : GR 878-C, BRIDGE ISOLATION TRANSFORMER  
 $C_S$ : GR 1409-T, STANDARD MICA CAPACITOR  
 $R_S$ : GR 1434-G, STANDARD DECADE RESISTOR

Figure 27. Bridge circuit for measurement of capacitance and dissipation factor at high frequencies.

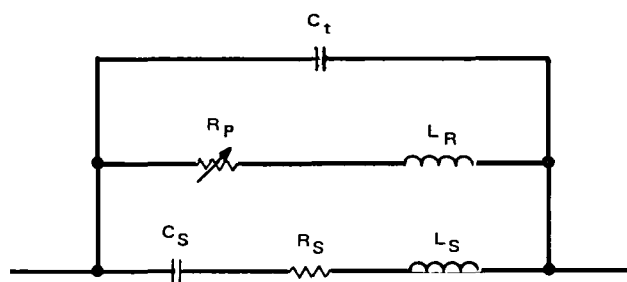


Figure 28. Equivalent circuit for  $C_S$  and  $R_P$  showing residual impedances.

Equation (1) yields  $C_{STD}$  the equivalent high frequency capacitance of  $C_s$ , and Equation (2) yields the equivalent series resistance  $R_{STD}$ .

$$C_{STD} = \left[ \frac{\omega^2 C_t - \frac{\omega^2 L_s - \frac{1}{C_s}}{R_s^2 + \left(\omega L_s - \frac{1}{\omega C_s}\right)^2} - \frac{\omega^2 L_r}{R_p^2 + (\omega L_r)^2}}{m} - \omega^2 L_c \right]^{-1} \quad (1)$$

$$R_{STD} = \frac{\frac{R_s}{R_s^2 + \left(\omega L_s - \frac{1}{\omega C_s}\right)^2} + \frac{R_p}{R_p^2 + (\omega L_r)^2}}{m} + R_c \quad (2)$$

where:

$$m = \left[ \frac{R_s}{R_s^2 + \left(\omega L_s - \frac{1}{\omega C_s}\right)^2} + \frac{R_p}{R_p^2 + (\omega L_r)^2} \right]^2 + \left[ \omega C_t - \frac{\omega L_s \frac{1}{\omega C_s}}{R_s^2 + \left(\omega L_s - \frac{1}{\omega C_s}\right)^2} - \frac{\omega L_r}{R_p^2 + (\omega L_r)^2} \right]^2$$

From the above results for  $C_{STD}$  and  $R_{STD}$ , the unknown capacitor values are obtained by Equations (3) and (4), where  $T$  is the setting of the bridge ratio transformer.

$$C_x = \left( \frac{1}{T} - 1 \right) C_{STD} \quad (3)$$

$$R_x = \frac{R_{STD}}{\left( \frac{1}{T} - 1 \right)} \quad (4)$$

While the decade resistor  $R_p$  is physically placed in parallel with  $C_s$  to obtain practical resistor values, the calculated result  $R_x$  is an equivalent series resistance that is more representative of capacitor performance. The DF was calculated from the values obtained for  $R_x$ .

The data for the capacitance and DF measurements versus frequency are presented in Tables 9 through 16. The extended frequency measurements at 10 Hz and 100 kHz are given in Table 17.

#### DC RESISTANCE

DC resistance was measured for each component at 25°C. The data for the 0.1  $\mu\text{F}$  capacitors are presented in Table 18. The data for the 2  $\mu\text{F}$  capacitors are presented in Table 19.

#### CORONA MEASUREMENTS

Measurement of corona has been routinely applied as a quality control technique on high voltage components such as transformers and cables and to a lesser extent on capacitors. With components that have relatively low inter-electrode capacitances, such tests have been successful, giving reliable nondestructive indications of maximum operating voltage and life at voltage. One problem with the testing of capacitors of large capacitance, such as those in this program, is sensitivity. The sensitivity problem affects both AC and DC measurements. A 60 kV Biddle (Figure 24) equipped with pulse counting facilities, Figure 25, was used in this program. Since it is a single-ended detector, the sensitivity is proportional to  $1/C_s$ , where  $C_s$  is the sample capacitance. A calculated sensitivity versus  $C_s$  curve for this equipment, derived from values supplied by Biddle, is shown in Figure 29. In practice, the sensitivity is somewhat better, being about 200 pC at 1  $\mu\text{F}$ .

The corona counter had eight channels set at 2, 5, 30, 50, 100, 300, 500 and 600 pC for the 0.1  $\mu\text{F}$  capacitor. For the 2  $\mu\text{F}$  capacitors the counter channels were set at 40, 50, 80, 100, 300, 500, 950 and 990 pC. The calibration pulse was 1000 pC. The 2  $\mu\text{F}$  capacitors required maximum gain in the amplifier and background noise was apparent.

TABLE 9. PARAMETER MEASUREMENTS AT 25°C

| Specimen | 120 Hz     |             | 1 kHz      |             | 10 kHz     |             |
|----------|------------|-------------|------------|-------------|------------|-------------|
|          | C, $\mu$ F | DF, percent | C, $\mu$ F | DF, percent | C, $\mu$ F | DF, percent |
| 150      | 0.0207     | 102.0       | 0.0185     | 27.2        | 0.0115     | 54.7        |
| 151      | 0.0781     | 1.0         | 0.0770     | 1.2         | 0.0769     | 2.7         |
| 152      | 0.0584     | 1.1         | 0.0574     | 1.4         | 0.0573     | 4.5         |
| 153      | 0.0911     | 1.1         | 0.0896     | 1.2         | 0.0894     | 2.8         |
| 154      | 0.0901     | 1.1         | 0.0886     | 1.3         | 0.0884     | 2.8         |
| 156      | 0.0000     | 200.0       | 0.0000     | 200.0       | 0.0000     | 18.3        |
| 157      | 0.0324     | 77.0        | 0.0319     | 9.2         | 0.0318     | 9.0         |
| 158      | 0.0629     | 1.1         | 0.0619     | 1.5         | 0.0617     | 5.6         |
| 159      | 0.0325     | 3.7         | 0.0318     | 5.7         | 0.0281     | 34.4        |
| 161      | 0.0951     | 1.1         | 0.0936     | 1.2         | 0.0934     | 2.8         |
| 162      | 0.0000     | 200.0       | 0.0000     | 13.9        | 0.0000     | 0.0         |
| 163      | 0.0563     | 1.1         | 0.0554     | 1.8         | 0.0549     | 8.7         |
| 41       | 0.0835     | 1.1         | 0.0821     | 1.3         | 0.0819     | 2.9         |
| 44       | 0.0618     | 1.1         | 0.0608     | 1.3         | 0.0606     | 2.8         |
| 45       | 0.0937     | 1.0         | 0.0922     | 1.2         | 0.0919     | 2.8         |
| 46       | 0.0716     | 1.0         | 0.0705     | 1.1         | 0.0704     | 2.6         |
| 48       | 0.0840     | 1.0         | 0.0827     | 1.3         | 0.0825     | 2.7         |
| 49       | 0.0786     | 1.0         | 0.0774     | 1.2         | 0.0771     | 2.7         |
| 239      | 1.797      | 1.2         | 1.765      | 2.3         | 1.766      | 12.3        |
| 242      | 1.619      | 2.3         | 1.570      | 13.3        | 1.139      | 44.0        |
| 243      | 1.756      | 1.1         | 1.726      | 1.5         | 1.757      | 4.0         |
| 244      | 1.767      | 1.5         | 1.732      | 5.8         | 1.475      | 28.2        |
| 247      | 1.767      | 1.1         | 1.737      | 1.5         | 1.766      | 4.4         |
| 248      | 1.772      | 1.1         | 1.742      | 1.6         | 1.767      | 4.9         |
| 250      | 1.775      | 1.1         | 1.745      | 1.6         | 1.779      | 4.8         |
| 253      | 1.800      | 1.1         | 1.769      | 1.6         | 1.796      | 4.8         |
| 254      | 1.767      | 1.1         | 1.738      | 1.5         | 1.766      | 4.3         |
| 255      | 1.667      | 1.8         | 1.629      | 9.0         | 1.242      | 33.7        |
| 256      | 1.691      | 1.2         | 1.662      | 2.8         | 1.638      | 15.6        |
| 257      | 1.729      | 1.1         | 1.700      | 1.5         | 1.728      | 4.4         |
| 19       | 1.818      | 1.2         | 1.787      | 3.3         | 1.749      | 19.6        |
| 20       | 1.920      | 1.4         | 1.887      | 1.6         | 1.930      | 4.6         |
| 23       | 1.880      | 1.4         | 1.851      | 1.4         | 1.880      | 3.3         |
| 25       | 1.890      | 1.0         | 1.863      | 1.4         | 1.910      | 3.8         |
| 21       | 1.880      | 1.5         | 1.847      | 1.5         | 1.880      | 4.1         |
| 29       | 1.890      | 1.5         | 1.857      | 1.5         | 1.900      | 4.5         |

TABLE 10. PARAMETER MEASUREMENTS AT 25°C

| Specimen | 120 Hz           |             | 1 kHz            |             | 10 kHz           |             |
|----------|------------------|-------------|------------------|-------------|------------------|-------------|
|          | C, $\mu\text{F}$ | DF, percent | C, $\mu\text{F}$ | DF, percent | C, $\mu\text{F}$ | DF, percent |
| 57       | 0.0529           | 0.9         | 0.0522           | 1.1         | 0.0521           | 2.6         |
| 58       | 0.0434           | 1.0         | 0.0428           | 1.5         | 0.0426           | 6.6         |
| 59       | 0.0780           | 1.0         | 0.0768           | 1.1         | 0.0767           | 2.7         |
| 60       | 0.0794           | 1.0         | 0.0782           | 1.2         | 0.0780           | 2.7         |
| 62       | 0.0814           | 1.0         | 0.0801           | 1.2         | 0.0799           | 2.9         |
| 63       | 0.0824           | 1.0         | 0.0811           | 1.2         | 0.0809           | 2.8         |
| 67       | 0.0193           | 85.0        | 0.0190           | 10.4        | 0.0188           | 7.9         |
| 4?       | 0.0760           | 1.0         | 0.0749           | 1.2         | 0.0746           | 2.8         |
| 5?       | 0.0590           | 0.9         | 0.0581           | 1.1         | 0.0581           | 3.1         |
| ?        | 0.0748           | 1.1         | 0.0736           | 1.3         | 0.0733           | 3.7         |
| 148      | 0.0914           | 1.1         | 0.0899           | 1.2         | 0.0897           | 2.8         |
| 149      | 0.0407           | 57.4        | 0.0401           | 7.3         | 0.0399           | 6.9         |
| 29       | 0.0787           | 1.0         | 0.0775           | 1.2         | 0.0733           | 2.7         |
| 32       | 0.0742           | 1.0         | 0.0730           | 1.2         | 0.0728           | 2.8         |
| 35       | 0.0599           | 0.9         | 0.0590           | 1.1         | 0.0589           | 2.7         |
| 36       | 0.0790           | 1.0         | 0.0779           | 1.2         | 0.0777           | 2.7         |
| 37       | 0.0578           | 1.0         | 0.0569           | 1.2         | 0.0567           | 2.7         |
| 39       | 0.0665           | 1.0         | 0.0655           | 1.2         | 0.0653           | 2.7         |
| 221      | 1.581            | 1.0         | 1.553            | 1.6         | 1.569            | 4.7         |
| 222      | 1.535            | 1.1         | 1.507            | 1.5         | 1.519            | 3.7         |
| 226      | 1.600            | 1.0         | 1.572            | 1.6         | 1.593            | 4.3         |
| 227      | 1.785            | 1.1         | 1.755            | 2.0         | 1.773            | 8.4         |
| 228      | 1.670            | 16.1        | 1.644            | 2.6         | 1.666            | 3.7         |
| 229      | 1.765            | 1.1         | 1.735            | 1.7         | 1.757            | 5.8         |
| 230      | 1.777            | 1.1         | 1.747            | 1.5         | 1.780            | 3.7         |
| 232      | 1.785            | 1.1         | 1.754            | 1.7         | 1.775            | 5.4         |
| 233      | 1.686            | 1.1         | 1.657            | 1.6         | 1.679            | 4.8         |
| 234      | 1.777            | 1.1         | 1.747            | 1.7         | 1.769            | 6.0         |
| 235      | 1.767            | 1.1         | 1.738            | 1.6         | 1.769            | 5.0         |
| 238      | 1.785            | 1.1         | 1.755            | 2.4         | 1.751            | 12.1        |
| 2        | 2.330            | 1.4         | 2.300            | 1.6         | 2.360            | 5.0         |
| 6        | 2.190            | 4.2         | 2.160            | 1.9         | 2.220            | 4.8         |
| 9        | 2.310            | 1.5         | 2.270            | 1.5         | 2.320            | 3.5         |
| 13       | 1.820            | 1.5         | 1.790            | 1.6         | 1.830            | 4.8         |
| 14       | 1.900            | 16.0        | 1.830            | 3.0         | 1.850            | 4.5         |
| 18       | 1.800            | 1.5         | 1.770            | 1.5         | 1.810            | 3.5         |

TABLE 11. PARAMETER MEASUREMENTS AT 25°C

| Specimen | 120 Hz     |             | 1 kHz      |             | 10 kHz     |             |
|----------|------------|-------------|------------|-------------|------------|-------------|
|          | C, $\mu$ F | DF, percent | C, $\mu$ F | DF, percent | C, $\mu$ F | DF, percent |
| 164      | 0.0853     | 1.0         | 0.0841     | 1.2         | 0.0839     | 3.1         |
| 166      | 0.0742     | 1.0         | 0.0731     | 1.2         | 0.0730     | 3.1         |
| 167      | 0.0300     | 200.0       | 0.0000     | 200.0       | 0.0000     | 0.0         |
| 168      | 0.0899     | 1.1         | 0.0886     | 1.3         | 0.0883     | 2.8         |
| 169      | 0.0123     | 1.0         | 0.0909     | 1.2         | 0.0906     | 2.8         |
| 170      | 0.0925     | 1.1         | 0.910      | 1.3         | 0.0907     | 2.8         |
| 171      | 0.0363     | 89.5        | 0.0358     | 10.9        | 0.0356     | 11.0        |
| 172      | 0.0886     | 1.0         | 0.0873     | 1.3         | 0.0871     | 3.0         |
| 173      | 0.0335     | 39.4        | 0.0326     | 8.8         | 0.0293     | 24.0        |
| 174      | 0.0823     | 1.0         | 0.0810     | 1.3         | 0.0808     | 3.3         |
| 87       | 0.0544     | 29.1        | 0.0087     | 237.0       | 0.0458     | 1980.0      |
| 88       | 0.0410     | 9.4         | 0.0405     | 2.4         | 0.0402     | 7.8         |
| 51       | 0.0762     | 1.0         | 0.750      | 1.2         | 0.0749     | 2.7         |
| 52       | 0.0755     | 1.0         | 0.744      | 1.1         | 0.0743     | 2.6         |
| 54       | 0.0624     | 1.0         | 0.0615     | 1.1         | 0.0614     | 2.6         |
| 55       | 0.0681     | 1.0         | 0.0671     | 1.1         | 0.0670     | 2.6         |
| 143      | 0.0842     | 1.2         | 0.0875     | 1.4         | 0.0872     | 2.9         |
| Open     | 0.0000     | 200.0       | 0.0000     | 200.0       | 0.0000     | 0.0         |
| 260      | 1.731      | 1.2         | 1.700      | 2.4         | 1.706      | 13.1        |
| 261      | 1.729      | 1.1         | 1.700      | 1.5         | 1.719      | 4.2         |
| 262      | 1.772      | 1.1         | 1.741      | 1.5         | 1.771      | 3.5         |
| 263      | 1.787      | 1.2         | 1.756      | 2.1         | 1.759      | 10.1        |
| 264      | 1.749      | 1.1         | 1.719      | 1.5         | 1.746      | 3.6         |
| 265      | 1.806      | 1.2         | 1.774      | 1.6         | 1.801      | 5.0         |
| 266      | 1.759      | 1.1         | 1.730      | 1.5         | 1.762      | 4.3         |
| 267      | 1.772      | 1.1         | 1.740      | 1.7         | 1.759      | 5.6         |
| 268      | 1.679      | 1.0         | 1.652      | 1.6         | 1.676      | 3.4         |
| 269      | 1.791      | 1.1         | 1.759      | 1.6         | 1.789      | 4.1         |
| 271      | 1.618      | 1.0         | 1.592      | 1.5         | 1.617      | 4.2         |
| 272      | 1.704      | 1.1         | 1.675      | 1.4         | 1.701      | 3.5         |
| 31       | 1.940      | 1.4         | 1.910      | 1.5         | 1.940      | 3.8         |
| 32       | 1.910      | 1.5         | 1.880      | 1.8         | 1.910      | 6.7         |
| 36       | 1.960      | 1.5         | 1.930      | 1.6         | 1.960      | 4.8         |
| 207      | 1.740      | 1.4         | 1.710      | 1.5         | 1.750      | 3.7         |
| 210      | 1.750      | 1.5         | 1.720      | 1.5         | 1.740      | 4.3         |
| 216      | 1.760      | 1.4         | 1.730      | 4.5         | 1.569      | 23.2        |

TABLE 12. PARAMETER MEASUREMENTS AT 25°C

| Specimen | 120 Hz |                | 1 kHz  |                | 10 kHz |                |
|----------|--------|----------------|--------|----------------|--------|----------------|
|          | C, F   | DF,<br>percent | C, F   | DF,<br>percent | C, F   | DF,<br>percent |
| 89       | 0.0747 | 1.1            | 0.0734 | 1.2            | 0.0732 | 2.8            |
| 90       | 0.0821 | 1.0            | 0.0809 | 1.2            | 0.0807 | 2.7            |
| 91       | 0.0613 | 1.0            | 0.0603 | 1.4            | 0.0601 | 5.0            |
| 92       | 0.0304 | 12.9           | 0.0299 | 3.1            | 0.0296 | 9.8            |
| 145      | 0.0845 | 1.2            | 0.0831 | 1.3            | 0.0823 | 2.8            |
| 147      | 0.0766 | 1.1            | 0.0753 | 1.3            | 0.0750 | 2.7            |
| 273      | 1.736  | 1.1            | 1.707  | 1.9            | 1.720  | 8.1            |
| 274      | 1.738  | 1.1            | 1.709  | 1.4            | 1.730  | 3.4            |
| 276      | 1.817  | 1.1            | 1.786  | 1.6            | 1.815  | 5.5            |
| 277      | 1.831  | 1.1            | 1.800  | 1.5            | 1.828  | 5.3            |
| 219      | 1.798  | 1.1            | 1.766  | 1.5            | 1.795  | 4.1            |
| 220      | 1.768  | 1.1            | 1.737  | 1.8            | 1.753  | 6.8            |



TABLE 13. PARAMETER MEASUREMENTS AT 25°C

| Specimen | 120 Hz     |             | 1 kHz      |             | 10 kHz     |             |
|----------|------------|-------------|------------|-------------|------------|-------------|
|          | C, $\mu$ F | DF, percent | C, $\mu$ F | DF, percent | C, $\mu$ F | DF, percent |
| 65       | 0.0717     | 1.0         | 0.0707     | 1.1         | 1.0706     | 2.6         |
| 66       | 0.0412     | 1.1         | 0.0405     | 1.5         | 0.0404     | 5.9         |
| 67       | 2000.0     | 200.0       | 2000.0     | 2000.0      | 200.0      | 2000.0      |
| 68       | 0.0732     | 0.9         | 0.0722     | 1.1         | 0.0721     | 2.6         |
| 70       | 0.0655     | 1.0         | 0.0645     | 1.2         | 0.0643     | 2.6         |
| 71       | 0.0693     | 1.0         | 0.0682     | 1.2         | 0.0681     | 2.6         |
| 72       | 0.0667     | 1.0         | 0.0658     | 1.1         | 0.0657     | 2.5         |
| 73       | 0.0564     | 1.0         | 0.0556     | 1.2         | 0.0555     | 3.1         |
| 74       | 0.0434     | 1.2         | 0.0427     | 2.7         | 0.0418     | 17.1        |
| 75       | 0.0643     | 1.0         | 0.0633     | 1.1         | 0.0632     | 2.7         |
| 76       | 0.0590     | 1.1         | 0.0581     | 2.0         | 0.0575     | 10.1        |
| 77       | 0.0646     | 1.0         | 0.0637     | 1.2         | 0.0536     | 3.2         |
| 78       | 0.0837     | 1.0         | 0.0825     | 1.1         | 0.0824     | 2.6         |
| 79       | 0.0454     | 1.1         | 0.0447     | 2.5         | 0.0437     | 15.2        |
| 80       | 0.0667     | 1.0         | 0.0657     | 1.2         | 0.0656     | 2.7         |
| 81       | 0.0855     | 1.0         | 0.0841     | 1.2         | 0.840      | 2.7         |
| 82       | 0.0756     | 1.0         | 0.0745     | 1.2         | 0.0744     | 2.6         |
| 83       | 0.0508     | 1.1         | 0.0598     | 1.5         | 0.0596     | 4.8         |
| 85       | 0.0593     | 1.0         | 0.0584     | 1.6         | 0.052      | 7.1         |
| 86       | 0.705      | 1.1         | 0.0693     | 1.3         | 0.0691     | 2.7         |
| 92       | 1.778      | 1.1         | 1.748      | 1.4         | 1.779      | 3.3         |
| 98       | 1.729      | 1.2         | 1.699      | 1.5         | 1.720      | 3.4         |
| 99       | 1.678      | 1.1         | 1.651      | 1.4         | 1.678      | 3.3         |
| 100      | 1.786      | 1.1         | 1.756      | 1.5         | 1.781      | 3.9         |
| 101      | 1.746      | 1.1         | 1.716      | 1.5         | 1.740      | 4.9         |
| 102      | 1.724      | 1.1         | 1.694      | 1.4         | 1.718      | 3.5         |
| 107      | 1.752      | 1.1         | 1.722      | 1.5         | 1.753      | 4.0         |
| 108      | 1.752      | 1.1         | 1.723      | 1.5         | 1.747      | 4.4         |
| 110      | 1.705      | 1.1         | 1.677      | 1.5         | 1.701      | 4.1         |
| 111      | 1.735      | 1.7         | 1.696      | 7.5         | 1.355      | 29.3        |
| 112      | 1.794      | 1.1         | 1.765      | 1.4         | 1.799      | 3.8         |
| 113      | 0.000      | 200.0       | 0.000      | 2000.0      | 0.000      | 0.0         |
| 114      | 1.726      | 1.1         | 1.696      | 1.4         | 1.725      | 3.4         |
| 115      | 1.732      | 1.1         | 1.708      | 1.4         | 1.738      | 4.1         |
| 118      | 1.762      | 1.1         | 1.732      | 1.4         | 1.759      | 3.6         |
| 119      | 1.841      | 1.0         | 1.811      | 1.5         | 1.855      | 4.1         |
| 121      | 1.732      | 1.1         | 1.703      | 1.5         | 1.728      | 4.3         |
| 139      | 1.746      | 1.2         | 1.716      | 1.6         | 1.745      | 5.7         |
| 140      | 1.739      | 1.1         | 1.708      | 1.4         | 1.742      | 3.6         |
| 200      | 1.712      | 1.4         | 1.678      | 5.3         | 1.459      | 22.4        |

TABLE 14. PARAMETER MEASUREMENTS AT 25°C

| Specimen | 120 Hz     |                | 1 kHz      |                | 10 kHz     |                |
|----------|------------|----------------|------------|----------------|------------|----------------|
|          | C, $\mu$ F | DF,<br>percent | C, $\mu$ F | DF,<br>percent | C, $\mu$ F | DF,<br>percent |
| 107      | 0.0525     | 1.2            | 0.517      | 3.5            | 0.0500     | 24.5           |
| 108      | 0.0720     | 1.0            | 0.0709     | 1.2            | 0.0708     | 2.5            |
| 110      | 0.0822     | 1.0            | 0.0809     | 1.2            | 0.0808     | 2.5            |
| 111      | 0.0508     | 1.0            | 0.0501     | 1.2            | 0.0500     | 2.8            |
| 112      | 0.0597     | 1.1            | 0.0588     | 1.5            | 0.0585     | 4.9            |
| 201      | 1.759      | 2.0            | 1.709      | 9.8            | 1.277      | 26.0           |
| 202      | 1.707      | 1.1            | 1.679      | 1.5            | 1.699      | 4.4            |
| 203      | 1.671      | 2.3            | 1.614      | 13.3           | 1.096      | 28.2           |
| 205      | 1.757      | 1.1            | 1.727      | 1.4            | 1.753      | 3.7            |
| OPEN     | 0.000      | 200.0          | 0.000      | 2000.0         | 0.000      | 0.0            |

TABLE 15. PARAMETER MEASUREMENTS AT 25°C

| Specimen | 120 Hz           |             | 1 kHz            |             | 10 kHz           |             |
|----------|------------------|-------------|------------------|-------------|------------------|-------------|
|          | C, $\mu\text{F}$ | DF, percent | C, $\mu\text{F}$ | DF, percent | C, $\mu\text{F}$ | DF, percent |
| 93       | 0.0809           | 1.0         | 0.0796           | 1.2         | 0.0795           | 2.5         |
| 94       | 0.0837           | 1.1         | 0.0823           | 1.2         | 0.0822           | 2.5         |
| 95       | 0.0281           | 3.5         | 0.0274           | 4.3         | 0.0261           | 27.2        |
| 96       | 0.0856           | 1.0         | 0.0842           | 1.3         | 0.0840           | 2.8         |
| 97       | 0.0342           | 1.2         | 0.0337           | 1.3         | 0.0336           | 3.3         |
| 98       | 0.0686           | 1.1         | 0.0675           | 1.3         | 0.0673           | 3.1         |
| 99       | 0.0541           | 1.0         | 0.0532           | 1.2         | 0.0532           | 3.7         |
| 100      | 0.0811           | 1.0         | 0.0798           | 1.3         | 0.0797           | 3.1         |
| 101      | 0.0810           | 1.0         | 0.0797           | 1.2         | 0.0795           | 2.7         |
| 102      | 0.0750           | 1.1         | 0.0738           | 1.2         | 0.0736           | 2.6         |
| 103      | 0.0787           | 1.1         | 0.0775           | 1.6         | 0.0773           | 7.0         |
| 104      | 0.0635           | 1.1         | 0.0625           | 2.0         | 0.0620           | 10.6        |
| 105      | 0.0696           | 1.1         | 0.0685           | 1.2         | 0.0684           | 2.6         |
| 106      | 0.0761           | 1.0         | 0.0749           | 1.2         | 0.0748           | 2.6         |
| 10       | 0.0925           | 1.2         | 0.0909           | 1.3         | 0.0907           | 2.7         |
| 11       | 0.0848           | 1.8         | 0.0826           | 2.0         | 0.0820           | 6.0         |
| 18       | 0.0903           | 1.1         | 0.0889           | 1.5         | 0.0887           | 5.6         |
| 19       | 0.0860           | 1.1         | 0.0846           | 1.3         | 0.0844           | 3.1         |
| 21       | 0.0922           | 1.3         | 0.0905           | 1.5         | 0.0902           | 3.4         |
| 23       | 0.0856           | 1.3         | 0.0842           | 1.3         | 0.0840           | 2.8         |
| 278      | 1.839            | 1.1         | 1.807            | 1.6         | 1.839            | 5.4         |
| 279      | 1.764            | 1.1         | 1.735            | 1.4         | 1.760            | 3.4         |
| 280      | 1.823            | 1.0         | 1.793            | 1.4         | 1.831            | 3.9         |
| 283      | 1.874            | 1.0         | 1.845            | 1.4         | 1.879            | 4.5         |
| 284      | 1.835            | 1.0         | 1.806            | 1.4         | 1.839            | 4.4         |
| 285      | 1.895            | 1.1         | 1.863            | 1.4         | 1.897            | 3.2         |
| 286      | 1.819            | 2.2         | 1.768            | 12.8        | 1.259            | 46.1        |
| 287      | 1.766            | 7.4         | 1.650            | 58.0        | 0.804            | 172.9       |
| 288      | 1.882            | 1.1         | 1.850            | 1.5         | 1.884            | 4.6         |
| 289      | 1.803            | 2.7         | 1.735            | 15.8        | 1.125            | 36.8        |
| 290      | 1.759            | 1.2         | 1.728            | 1.6         | 1.755            | 5.5         |
| 291      | 1.776            | 1.1         | 1.745            | 1.6         | 1.775            | 5.2         |
| 292      | 1.774            | 1.1         | 1.744            | 1.3         | 1.776            | 3.3         |
| 293      | 1.762            | 1.1         | 1.734            | 2.1         | 1.755            | 10.5        |
| 295      | 1.769            | 1.0         | 1.740            | 2.3         | 1.768            | 3.2         |
| 24       | 1.736            | 1.1         | 1.707            | 1.4         | 1.745            | 3.6         |
| 37       | 1.752            | 1.1         | 1.723            | 1.5         | 1.750            | 4.6         |
| 38       | 1.716            | 1.2         | 1.688            | 2.7         | 1.693            | 16.2        |
| 42       | 1.748            | 1.1         | 1.718            | 1.5         | 1.752            | 4.3         |
| 47       | 1.772            | 1.1         | 1.743            | 1.6         | 1.772            | 5.9         |

TABLE 16. PARAMETER MEASUREMENTS AT 25° C

| Specimen | 120 Hz     |             | 1 kHz      |             | 10 kHz     |             |
|----------|------------|-------------|------------|-------------|------------|-------------|
|          | C, $\mu$ F | DF, percent | C, $\mu$ F | DF, percent | C, $\mu$ F | DF, percent |
| 113      | 0.0483     | 1.3         | 0.0474     | 3.3         | 0.0465     | 22.0        |
| 114      | 0.0768     | 1.2         | 0.0753     | 1.4         | 0.0751     | 2.6         |
| 115      | 0.0641     | 1.0         | 0.0630     | 1.3         | 0.0629     | 3.9         |
| 117      | 0.0745     | 1.1         | 0.0732     | 1.2         | 0.0731     | 2.8         |
| 118      | 0.0812     | 1.1         | 0.0798     | 1.3         | 0.0796     | 3.2         |
| 119      | 0.0559     | 1.1         | 0.0549     | 1.4         | 0.0548     | 4.2         |
| 120      | 0.0713     | 1.0         | 0.0702     | 1.4         | 0.0701     | 5.7         |
| 121      | 0.0819     | 1.0         | 0.0805     | 1.2         | 0.0805     | 2.7         |
| 122      | 0.0710     | 1.0         | 0.0699     | 1.7         | 0.0695     | 7.9         |
| 123      | 0.0811     | 1.0         | 0.0799     | 1.2         | 0.0798     | 2.9         |
| 125      | 0.0000     | 200.0       | 0.0000     | 200.0       | 0.0000     | 0.0         |
| 126      | 0.0457     | 1.3         | 0.0449     | 3.8         | 0.0430     | 26.3        |
| 127      | 0.0752     | 1.0         | 0.0740     | 1.2         | 0.0739     | 2.6         |
| 128      | 0.0512     | 1.0         | 0.0504     | 1.3         | 0.0503     | 3.6         |
| 129      | 0.0594     | 1.2         | 0.0585     | 2.6         | 0.0575     | 16.5        |
| 131      | 0.0649     | 1.1         | 0.0639     | 1.5         | 0.0637     | 5.0         |
| 132      | 0.0906     | 1.1         | 0.0891     | 1.2         | 0.0890     | 2.6         |
| 133      | 0.0541     | 1.1         | 0.0532     | 1.6         | 0.0530     | 5.8         |
| 134      | 0.0726     | 1.1         | 0.0715     | 1.4         | 0.0713     | 4.5         |
| 135      | 0.0869     | 1.0         | 0.0856     | 1.2         | 0.0855     | 2.5         |
| 49       | 1.930      | 1.5         | 1.897      | 1.8         | 1.920      | 7.1         |
| 51       | 1.920      | 1.0         | 1.882      | 1.4         | 1.910      | 3.7         |
| 52       | 1.887      | 1.1         | 1.855      | 1.5         | 1.890      | 4.2         |
| 54       | 1.831      | 1.1         | 1.799      | 1.5         | 1.830      | 3.4         |
| 57       | 1.910      | 40.4        | 1.874      | 1.4         | 1.910      | 3.3         |
| 58       | 1.880      | 35.9        | 1.846      | 1.4         | 1.880      | 3.9         |
| 59       | 1.920      | 0.0         | 1.889      | 1.5         | 1.930      | 4.3         |
| 61       | 1.880      | 0.3         | 1.846      | 1.5         | 1.880      | 3.4         |
| 62       | 1.898      | 1.1         | 1.866      | 1.5         | 1.900      | 4.0         |
| 67       | 1.734      | 1.1         | 1.704      | 1.4         | 1.730      | 3.3         |
| 68       | 1.810      | 1.2         | 1.778      | 1.4         | 1.810      | 3.2         |
| 69       | 1.772      | 1.1         | 1.742      | 1.5         | 1.770      | 3.3         |
| 70       | 1.756      | 1.1         | 1.727      | 1.5         | 1.750      | 4.2         |
| 71       | 1.745      | 1.1         | 1.716      | 1.4         | 1.750      | 3.2         |
| 72       | 1.827      | 1.1         | 1.797      | 1.5         | 1.820      | 4.3         |
| 73       | 1.774      | 1.2         | 1.743      | 1.4         | 1.780      | 3.2         |
| 74       | 1.779      | 1.1         | 1.750      | 1.4         | 1.780      | 3.7         |
| 78       | 1.777      | 1.4         | 1.744      | 4.4         | 1.596      | 23.8        |
| 79       | 1.778      | 1.1         | 1.748      | 1.4         | 1.784      | 3.5         |
| 80       | 1.806      | 1.1         | 1.776      | 1.4         | 1.814      | 3.6         |

TABLE 17. EXTENDED FREQUENCY MEASUREMENTS

| Specimen            | 10 Hz      |             | 100 kHz    |             | Specimen | 10 Hz      |             | 100 kHz    |             |
|---------------------|------------|-------------|------------|-------------|----------|------------|-------------|------------|-------------|
|                     | C, $\mu$ F | DF, percent | C, $\mu$ F | DF, percent |          | C, $\mu$ F | DF, percent | C, $\mu$ F | DF, percent |
| 29                  | 0.080734   | 1.52        | 0.0739     | 7.8         | 2        | 2.3917     | 1.61        | 2.175      | 17.0        |
| 30*                 | 0.011095   | 7.78        | 0.0103     | 26.6        | 6*       | 2.2503     | 18.88       | 2.073      | 19.0        |
| 32                  | 0.076101   | 1.56        | 0.0696     | 7.8         | 9        | 2.3750     | 1.68        | 2.302      | 12.0        |
| 35                  | 0.061301   | 1.42        | 0.0565     | 8.5         | 13       | 1.8724     | 1.67        | 1.703      | 18.0        |
| 36                  | 0.080998   | 1.45        | 0.0747     | 7.3         | 14*      | 1.9051     | 33.25       | 1.709      | 15.0        |
| 37                  | 0.059481   | 1.52        | 0.0548     | 7.5         | 18       | 1.8471     | 1.57        | 1.756      | 14.0        |
| 39                  | 0.068315   | 1.49        | 0.0631     | 7.3         | 19       | 1.8729     | 1.64        | 1.360      | 60.0        |
| 41                  | 0.085522   | 1.71        | 0.0783     | 7.8         | 20       | 1.9545     | 1.65        | 1.759      | 21.0        |
| 42*                 | 0.034361   | 2.05        | 0.0322     | 9.1         | 23       | 1.9229     | 1.63        | 1.828      | 12.0        |
| 44                  | 0.063261   | 1.55        | 0.0583     | 8.3         | 25       | 1.9281     | 1.62        | 1.830      | 15.0        |
| 45                  | 0.096252   | 1.54        | 0.0885     | 7.4         | 27       | 1.9252     | 1.69        | 1.803      | 20.0        |
| 46                  | 0.073227   | 1.45        | 0.0677     | 7.2         | 29       | 1.9386     | 1.72        | 1.782      | 22.0        |
| 47*                 | 0.034005   | 1.72        | 0.0319     | 12.0        | 31       | 1.9821     | 1.59        | 1.868      | 15.0        |
| 48                  | 0.086072   | 1.54        | 0.0790     | 7.5         | 32       | 1.9555     | 1.69        | 1.663      | 22.0        |
| 49                  | 0.080651   | 1.53        | 0.0746     | 6.7         | 36       | 1.9953     | 1.60        | 1.811      | 17.0        |
| 51                  | 0.078143   | 1.50        | 0.0722     | 7.2         | 207      | 1.7832     | 1.65        | 1.684      | 14.0        |
| 52                  | 0.077338   | 1.44        | 0.0717     | 6.9         | 210      | 1.7927     | 1.67        | 1.639      | 16.0        |
| 54                  | 0.063875   | 1.46        | 0.0592     | 7.4         | 216      | 1.8097     | 1.64        | 1.356      | 38.0        |
| 55                  | 0.069470   | 1.44        | 0.0644     | 7.3         | 219      | 1.8576     | 1.66        | 1.772      | 12.0        |
| 56*                 | 0.039460   | 1.52        | 0.0370     | 10.0        | 220      | 1.8271     | 1.66        | 1.555      | 21.0        |
| *Removed from test. |            |             |            |             |          |            |             |            |             |

TABLE 18. DIRECT CURRENT RESISTANCE  
OF 0.1  $\mu$ F CAPACITOR AT 25°C

| Specimen | G $\Omega$ | Specimen | G $\Omega$ | Specimen | G $\Omega$ | Specimen | G $\Omega$ |
|----------|------------|----------|------------|----------|------------|----------|------------|
| 57       | 10.3965    | 46       | 15.6561    | 72       | 22.9977    | 106      | 5.0205     |
| 58       | 11.4975    | 48       | 15.2357    | 73       | 24.4279    | 10       | 5.7066     |
| 59       | 17.2982    | 49       | 16.7813    | 74       | 0.0010     | 14       | 0.0010     |
| 60       | 16.3787    |          |            | 75       | 13.5187    | 18       | 3.0316     |
| 62       | 15.7357    | 164      | 10.8084    | 76       | 0.0263     | 19       | 6.8931     |
| 63       | 13.8095    | 166      | 9.6538     | 77       | 19.2776    | 21       | 16.6496    |
| 67       | 0.0010     | 167      | 4.3728     | 78       | 19.7824    | 23       | 6.2048     |
| 4?       | 18.8456    | 168      | 7.0216     | 79       | 0.0010     |          |            |
| 5?       | 16.7687    | 169      | 0.0521     | 80       | 20.3734    | 113      | 13.9721    |
| ?        | 15.0626    | 170      | 9.0471     | 81       | 15.1030    | 114      | 15.7658    |
| 148      | 11.1312    | 171      | 0.0011     | 82       | 14.7714    | 115      | 6.5238     |
| 149      | skipped    | 172      | 15.5513    | 83       | 21.6777    | 117      | 20.7803    |
| 29       | 13.6113    | 173      | 0.0011     | 85       | 0.0011     | 118      | 12.7837    |
| 32       | 0.0215     | 174      | 7.0920     | 86       | 22.3690    | 119      | 22.3642    |
| 35       | 17.7924    | 87       | 14.8735    |          |            | 120      | 20.6664    |
| 36       | 17.8753    | 88       | 0.0011     | 107      | 15.5577    | 121      | 3.8889     |
| 37       | 22.3684    | 51       | 13.9708    | 108      | 0.0010     | 122      | 16.0445    |
| 39       | 12.8319    | 52       | 14.4251    | 110      | 14.2733    | 123      | skipped    |
|          |            | 54       | 5.3591     | 111      | 26.5262    | 126      | 25.6410    |
| 150      | 0.001      | 55       | 9.6044     | 112      | 14.3651    | 127      | 14.0805    |
| 151      | 2.2478     | 143      | 10.6064    |          |            | 128      | 21.9534    |
| 152      | 0.0011     |          |            | 93       | 20.6068    | 129      | 0.7339     |
| 153      | 0.5314     | 89       | 9.1266     | 94       | 23.0009    | 131      | 34.1702    |
| 154      | 10.2263    | 90       | 11.9961    | 95       | 0.0010     | 132      | 16.3934    |
| 156      | 4.9939     | 91       | 14.5628    | 96       | 24.2800    | 133      | 0.0204     |
| 157      | 0.0010     | 92       | 0.0011     | 97       | 0.0010     | 134      | 10.9010    |
| 158      | 0.9042     | 145      | 5.8703     | 98       | 4.6571     | 135      | 17.0732    |
| 159      | skipped    | 147      | 3.9103     | 99       | 32.1499    |          |            |
| 161      | 15.0246    |          |            | 100      | 17.8142    | 136      | 13.5359    |
| 162      | 0.0011     | 65       | 20.0326    | 101      | 15.4113    | 137      | 1.4332     |
| 163      | 12.5547    | 66       | 25.3485    | 102      | 17.2183    | 140      | 6.1350     |
| 41       | 5.3165     | 68       | 0.0368     | 103      | 23.3971    | 141      | 0.0010     |
| 44       | 13.9989    | 70       | 31.3138    | 104      | 0.0010     | 142      | 20.1729    |
| 45       | 19.7331    | 71       | 0.2348     | 105      | 4.2046     |          |            |

TABLE 19. DIRECT CURRENT RESISTANCE OF 2  $\mu$ F CAPACITOR AT 25°C

| Specimen | G $\Omega$ | Specimen | G $\Omega$ | Specimen | G $\Omega$ | Specimen | G $\Omega$ |
|----------|------------|----------|------------|----------|------------|----------|------------|
| 221      | 1.4026     | 20       | 0.0109     | 92       | 0.0010     | 295      | 1.8335     |
| 222      | 1.0607     | 23       | 1.0135     | 98       | 1.8788     | 24       | 0.1070     |
| 226      | 1.3317     | 25       | 0.0049     | 99       | 0.0674     | 37       | 0.1854     |
| 227      | 1.2098     | 27       | 1.2097     | 100      | 1.8505     | 38       | 0.0010     |
| 228      | 0.0010     | 29       | 1.3903     | 101      | 1.7670     | 42       | 1.6944     |
| 229      | 1.3042     |          |            | 102      | 0.3086     | 47       | 1.6885     |
| 230      | 1.2331     | 260      | 1.6122     | 107      | 1.6177     |          |            |
| 232      | 1.2687     | 261      | 1.5428     | 108      | 1.6437     | 49       | 0.5517     |
| 233      | 0.0756     | 262      | 1.6207     | 110      | 1.9163     | 51       | 0.5479     |
| 234      | skipped    | 263      | 1.6032     | 111      | skipped    | 52       | 1.7266     |
| 235      | 1.1975     | 264      | 1.4084     | 112      | 1.4728     | 54       | 1.7370     |
| 238      | 0.6263     | 265      | 1.2900     | 114      | 1.6984     | 59       | 1.5771     |
| 2        | 1.0249     | 266      | 1.1594     | 115      | 1.6908     | 61       | 1.6476     |
| 6        | 0.0010     | 267      | 1.6116     | 118      | 1.7975     | 62       | 1.7988     |
| 9        | 0.7396     | 268      | 0.1518     | 119      | 1.5740     | 67       | 1.9927     |
| 13       | 0.0582     | 269      | 1.1278     | 121      | 1.3528     | 68       | 0.9261     |
| 14       | 0.0010     | 271      | 1.7935     | 130      | 1.2939     | 69       | 1.7327     |
| 18       | 1.3608     | 272      | 1.5245     | 140      | 0.0289     | 70       | 1.8229     |
|          |            | 31       | 0.3526     | 200      | 1.1656     | 71       | 1.9514     |
| 239      | 1.4855     | 32       | 1.1402     |          |            | 72       | 1.8963     |
| 242      | 1.3182     | 36       | 0.0874     | 278      | 1.8253     | 73       | 1.8297     |
| 243      | 1.2702     | 207      | 1.3689     | 279      | 1.8439     | 74       | 1.8882     |
| 244      | 1.3279     | 210      | 0.9228     | 280      | 1.9694     | 78       | 1.7877     |
| 247      | 1.4340     | 216      | 1.3915     | 283      | 1.1420     | 79       | 1.9679     |
| 248      | 1.2191     |          |            | 284      | 1.9005     | 80       | 1.8270     |
| 250      | 1.4606     | 273      | 1.4783     | 285      | 2.0435     |          |            |
| 253      | 1.4311     | 274      | 1.0056     | 288      | skipped    | 87       | 0.0224     |
| 254      | 48.8000    | 276      | 1.1705     | 290      | 1.9412     | 88       | 0.0059     |
| 255      | 1.6343     | 277      | 1.2176     | 291      | 2.0016     | 89       | 1.6967     |
| 256      | 1.4120     | 219      | 0.0332     | 292      | 0.6739     | 90       | 1.8449     |
| 257      | 1.4620     | 220      | 1.2812     | 293      | 1.9584     | 91       | 1.6295     |
| 19       | 1.4624     |          |            |          |            |          |            |

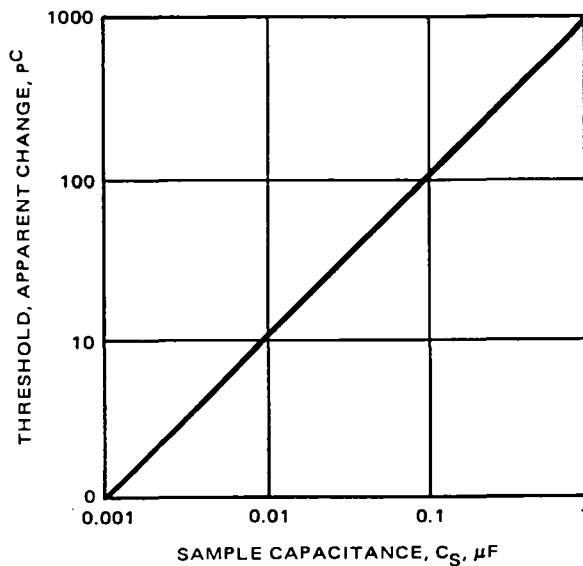


Figure 29. Corona test set sensitivity.

Eighteen 0.1  $\mu\text{F}$  capacitors and twenty-two 2  $\mu\text{F}$  capacitors were measured for corona. Measurements were made with 40 VAC first. Then the capacitors were tested with 40 VAC plus DC. The AC voltage was applied first. Then the DC was applied and slowly increased from 0 to 600 VDC. Fifteen of the 0.1  $\mu\text{F}$  capacitors tested showed no corona; three had a few counts. There were no failures. One 2  $\mu\text{F}$  capacitor failed corona at 40 VAC. Additional failures occurred on the AC plus DC corona test. Three occurred at 600 volts and one each at 460, 500 and 530 volts.

## DISCUSSION OF RESULTS

Capacitance versus frequency measurements exhibited a slight decrease in capacitance with increasing frequency over the range of 120 Hz to 10 kHz. This rate was consistent with the change in dielectric constant of KF film with frequency, see Figure 10a.

DF versus frequency measurements showed a large increase in the dissipation factor with increasing frequency over the range 120 Hz to 100 kHz. This rate is consistent with the change in dissipation factor of KF film with frequency, see Figure 11a. At 100 kHz the DF for the capacitors was consistent with the KF film data.



Some of the components have an excessively high DF at high frequency because of the termination connection. A high frequency DF measurement should be a good selection method. The insulation resistance appears to be adequate. Several failures were caused by the high DC potential.

Corona measurements were made with 40 VAC followed by 40 VAC plus 0 to 600 VDC. The 0.1  $\mu$ F capacitors showed no corona. Catastrophic breakdown caused 20 percent of the 2  $\mu$ F capacitors to fail.



## VI. LOW TEMPERATURE TESTS

### MEASUREMENTS

The low temperature testing was simple and straightforward. The requirements were:

1. 40 capacitors, 20 each type
2. 500 VDC applied
3. 48 hours at  $-3^{\circ}\text{C}$
4. 48 hours at  $-55^{\circ}\text{C}$  after  $-3^{\circ}\text{C}$ .

The capacitance, dissipation factor, and insulation resistance were measured at  $-3^{\circ}\text{C}$  and  $-55^{\circ}\text{C}$ , after each 48 hour exposure. In addition, measurements were made at  $25^{\circ}\text{C}$  and  $125^{\circ}\text{C}$ . The capacitance and DF were measured at 120 Hz, 1 kHz, and 10 kHz. These data are presented in Tables 20 through 23. The insulation resistance (IR) measurements are given in Tables 24 and 25.

### DISCUSSION OF RESULTS

The results of the low temperature tests are summarized in Table 26. It is evident that most of the failures were after the  $-3^{\circ}\text{C}$  exposure. Additional failures occurred after exposure at  $-55^{\circ}\text{C}$  and  $25^{\circ}\text{C}$ . Since there had been no previous screening to eliminate weak components the failures were probably caused by infant mortality. The failures appear to be rate sensitive.

The insulation resistance test was performed after each low temperature exposure, and it is of interest that no failures occurred.

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TABLE 20. LOW TEMPERATURE PARAMETER  
MEASUREMENTS AT -3°C

| Specimen | 120 Hz     |             | 1 kHz      |             | 10 kHz     |             |
|----------|------------|-------------|------------|-------------|------------|-------------|
|          | C, $\mu$ F | DF, percent | C, $\mu$ F | DF, percent | C, $\mu$ F | DF, percent |
| 93       | 0.0772     | 1.6         | 0.0747     | 4.3         | 0.0692     | 12.6        |
| 94       | 0.0914     | 11.7        | 0.0782     | 8.7         | 0.0713     | 13.4        |
| 95       | 0.0247     | 61.3        | 0.0058     | 126.3       | 0.0004     | 412.0       |
| 96       | 0.0960     | 0.0         | 0.1582     | 13.9        | 1.8350     | 11.8        |
| 97       | 0.0010     | 200.0       | 0.0000     | 200.0       | 0.1821     | 0.0         |
| 98       | 0.0656     | 1.7         | 0.0634     | 4.5         | 0.0586     | 13.2        |
| 99       | 0.0517     | 1.6         | 0.0501     | 4.5         | 0.0462     | 15.0        |
| 100      | 0.0770     | 1.8         | 0.0743     | 4.6         | 0.0685     | 13.1        |
| 101      | 0.0856     | 10.6        | 0.0770     | 10.0        | 0.0689     | 14.5        |
| 102      | 0.0858     | 14.1        | 0.0741     | 13.9        | 0.0646     | 16.0        |
| 103      | 0.0844     | 14.0        | 0.0753     | 12.0        | 0.0679     | 18.9        |
| 104      | 0.0102     | 113.7       | 0.0040     | 157.3       | 0.0008     | 318.0       |
| 105      | 0.0663     | 1.7         | 0.0646     | 7.8         | 0.0603     | 15.6        |
| 106      | 0.0726     | 1.7         | 0.0701     | 4.4         | 0.0656     | 14.5        |
| 10       | 0.0878     | 1.9         | 0.0847     | 4.5         | 0.0785     | 12.9        |
| 14       | 0.0000     | 200.0       | 0.0000     | 200.0       | 0.0000     | 0.0         |
| 18       | 0.0857     | 1.8         | 0.0827     | 4.7         | 0.0763     | 14.3        |
| 19       | 0.0815     | 1.8         | 0.0786     | 4.6         | 0.0726     | 13.1        |
| 21       | 0.0870     | 1.8         | 0.0839     | 4.7         | 0.0775     | 14.2        |
| 23       | 0.0600     | 200.0       | 0.0577     | 568.0       | 0.1513     | 0.0         |
| 278      | 1.671      | 1.6         | 1.621      | 4.2         | 1.54       | 14.2        |
| 279      | 1.692      | 1.6         | 1.641      | 4.1         | 1.56       | 12.9        |
| 280      | 1.692      | 1.6         | 1.641      | 4.0         | 1.46       | 12.5        |
| 283      | 1.674      | 1.7         | 1.623      | 5.9         | 1.54       | 24.7        |
| 284      | 1.680      | 1.6         | 1.628      | 4.2         | 1.54       | 12.9        |
| 285      | 1.646      | 1.6         | 1.593      | 4.4         | 1.50       | 13.3        |
| 286      | 0.000      | 200.0       | 0.000      | 200.0       | 20.0       | 200.0       |
| 287      | 0.000      | 200.0       | 0.000      | 200.0       | 20.0       | 200.0       |
| 288      | 1.655      | 1.7         | 1.601      | 4.6         | 1.50       | 14.3        |
| 289      | 0.000      | 200.0       | 0.000      | 23.4        | 20.0       | 200.0       |
| 290      | 1.750      | 1.5         | 1.699      | 4.0         | 1.62       | 13.0        |
| 291      | 1.684      | 1.5         | 1.635      | 3.9         | 1.55       | 12.1        |
| 292      | 1.739      | 1.5         | 1.689      | 4.0         | 1.61       | 12.5        |
| 293      | 1.791      | 1.4         | 1.741      | 4.0         | 1.66       | 12.7        |
| 295      | 1.753      | 1.5         | 1.703      | 4.2         | 1.61       | 13.4        |
| 24       | 1.802      | 1.6         | 1.746      | 4.2         | 1.66       | 12.7        |
| 37       | 1.720      | 4.7         | 1.588      | 31.7        | 0.81       | 57.7        |
| 38       | 0.000      | 200.0       | 0.000      | 200.0       | 20.0       | 200.0       |
| 42       | 1.784      | 1.6         | 1.728      | 4.4         | 1.63       | 14.0        |
| 47       | 1.610      | 24.8        | 1.555      | 215.0       | 20.0       | 200.0       |

TABLE 21. LOW TEMPERATURE PARAMETER  
MEASUREMENTS AT -55°C

| Specimen | 120 Hz     |             | 1 kHz      |             | 10 kHz     |             |
|----------|------------|-------------|------------|-------------|------------|-------------|
|          | C, $\mu$ F | DF, percent | C, $\mu$ F | DF, percent | C, $\mu$ F | DF, percent |
| 93       | 0.0305     | 4.0         | 0.0286     | 4.3         | 0.0273     | 4.1         |
| 94       | 0.0314     | 4.0         | 0.0295     | 4.2         | 0.0281     | 4.2         |
| 95       | 0.0000     | 200.0       | 0.0000     | 200.0       | 0.0000     | 0.0         |
| 96       | 0.0319     | 4.0         | 0.0299     | 4.2         | 0.0286     | 4.1         |
| 97       | 0.0000     | 200.0       | 0.0000     | 200.0       | 0.0000     | 0.0         |
| 98       | 0.0256     | 4.2         | 0.0240     | 4.5         | 0.0229     | 6.2         |
| 99       | 0.0201     | 4.2         | 0.0188     | 4.6         | 0.0179     | 6.9         |
| 100      | 0.0305     | 4.1         | 0.0286     | 4.4         | 0.0273     | 5.0         |
| 101      | 0.0306     | 4.1         | 0.0287     | 4.3         | 0.0273     | 4.3         |
| 102      | 0.0280     | 4.1         | 0.0262     | 4.3         | 0.0250     | 4.3         |
| 103      | 0.0296     | 4.1         | 0.0277     | 5.8         | 0.0263     | 19.2        |
| 104      | 0.0000     | 200.0       | 0.0000     | 200.0       | 0.0000     | 0.0         |
| 105      | 0.0260     | 4.0         | 0.0244     | 4.2         | 0.0233     | 4.0         |
| 106      | 0.0285     | 4.0         | 0.0268     | 4.2         | 0.0256     | 4.1         |
| 10       | 0.0342     | 4.0         | 0.0321     | 4.2         | 0.0306     | 4.2         |
| 14       | 0.0000     | 200.0       | 0.0000     | 200.0       | 0.0000     | 0.0         |
| 18       | 0.0337     | 3.9         | 0.0317     | 4.5         | 0.0302     | 6.3         |
| 19       | 0.0320     | 4.0         | 0.0301     | 4.2         | 0.0287     | 4.4         |
| 21       | 200.0      | 200.0       | 20.0       | 200.0       | 0.0609     | 471.0       |
| 23       | 0.0001     | 200.0       | 0.0002     | 2000.0      | 0.0001     | 849.0       |
| 278      | 0.681      | 4.6         | 0.635      | 5.0         | 0.600      | 2000.0      |
| 279      | 0.693      | 4.6         | 0.646      | 5.0         | 0.610      | 2000.0      |
| 280      | 0.694      | 4.6         | 0.646      | 5.0         | 0.610      | 2000.0      |
| 283      | 0.685      | 4.7         | 0.638      | 5.6         | 0.600      | 2000.0      |
| 284      | 0.687      | 4.6         | 0.640      | 5.0         | 0.610      | 2000.0      |
| 285      | 0.674      | 4.5         | 0.629      | 4.9         | 0.600      | 2000.0      |
| 286      | 0.000      | 200.0       | 0.000      | 200.0       | 20.0       | 2000.0      |
| 287      | 0.000      | 200.0       | 0.000      | 200.0       | 20.0       | 2000.0      |
| 288      | 0.000      | 200.0       | 0.000      | 200.0       | 20.0       | 2000.0      |
| 289      | 0.000      | 200.0       | 0.000      | 200.0       | 20.0       | 2000.0      |
| 290      | 0.733      | 5.0         | 0.679      | 5.4         | 0.640      | 2000.0      |
| 291      | 0.707      | 5.1         | 0.655      | 5.4         | 0.620      | 2000.0      |
| 292      | 0.726      | 5.1         | 0.672      | 5.4         | 0.630      | 2000.0      |
| 293      | 0.734      | 5.0         | 0.680      | 5.4         | 0.640      | 2000.0      |
| 295      | 0.708      | 4.7         | 0.658      | 5.1         | 0.620      | 2000.0      |
| 24       | 0.733      | 4.4         | 0.685      | 4.8         | 0.650      | 2000.0      |
| 37       | 0.501      | 61.8        | 0.644      | 555.0       | 20.0       | 2000.0      |
| 38       | 0.000      | 200.0       | 0.000      | 2000.0      | 20.0       | 2000.0      |
| 42       | 0.709      | 4.1         | 0.665      | 4.6         | 0.630      | 2000.0      |
| 47       | 0.681      | 5.0         | 0.639      | 13.7        | 0.580      | 2000.0      |

TABLE 22. LOW TEMPERATURE PARAMETER  
MEASUREMENTS AT 25°C

| Specimen | 120 Hz     |             | 1 kHz      |             | 10 kHz     |             |
|----------|------------|-------------|------------|-------------|------------|-------------|
|          | C, $\mu$ F | DF, percent | C, $\mu$ F | DF, percent | C, $\mu$ F | DF, percent |
| 93       | 0.0825     | 1.2         | 0.0812     | 1.3         | 0.0811     | 2.1         |
| 94       | 0.0851     | 1.2         | 0.0836     | 1.3         | 0.0836     | 2.1         |
| 95       | 0.0000     | 200.0       | 0.0000     | 24.5        | 0.0000     | 63.2        |
| 96       | 0.0880     | 0.0         | 0.1970     | 174.0       | 2.0000     | 200.0       |
| 97       | 0.01146    | 0.0         | 0.0001     | 2000.0      | 0.0220     | 0.0         |
| 98       | 0.0706     | 2.9         | 0.0690     | 1.6         | 0.0688     | 3.1         |
| 99       | 0.0550     | 1.1         | 0.0542     | 1.5         | 0.0541     | 4.9         |
| 100      | 0.0825     | 1.2         | 0.0812     | 1.3         | 0.0811     | 2.7         |
| 101      | 0.0825     | 1.3         | 0.0812     | 1.3         | 0.0811     | 2.3         |
| 102      | 0.0764     | 1.2         | 0.0752     | 1.3         | 0.0751     | 2.1         |
| 103      | 0.0800     | 1.2         | 0.0788     | 1.7         | 0.0787     | 6.6         |
| 104      | 0.0000     | 200.0       | 0.0000     | 21.9        | 0.0000     | 27.0        |
| 105      | 0.0708     | 1.2         | 0.0697     | 1.2         | 0.0696     | 2.2         |
| 106      | 0.0776     | 1.2         | 0.0764     | 1.2         | 0.0764     | 2.1         |
| 10       | 0.0942     | 2.1         | 0.0925     | 1.4         | 0.0924     | 2.3         |
| 14       | 0.0000     | 200.0       | 0.0000     | 33.5        | 0.0000     | 75.7        |
| 18       | 0.0918     | 1.2         | 0.0904     | 1.5         | 0.0903     | 4.3         |
| 19       | 0.0873     | 1.2         | 0.0859     | 1.3         | 0.0859     | 2.6         |
| 21       | 0.0937     | 1.5         | 0.0919     | 1.7         | 0.0918     | 4.3         |
| 23       | 0.0660     | 200.0       | 0.0636     | 527.0       | 0.0811     | 54.4        |
| 278      | 1.784      | 1.3         | 1.753      | 1.6         | 1.790      | 5.0         |
| 279      | 1.805      | 1.3         | 1.774      | 1.5         | 1.810      | 3.6         |
| 280      | 1.802      | 1.2         | 1.773      | 1.4         | 1.820      | 2.9         |
| 283      | 1.787      | 1.4         | 1.756      | 3.6         | 1.660      | 17.0        |
| 284      | 1.796      | 1.2         | 1.767      | 1.3         | 1.810      | 2.8         |
| 285      | 1.761      | 1.2         | 1.733      | 1.4         | 1.770      | 3.2         |
| 286      | 0.000      | 200.0       | 0.000      | 200.0       | 20.0       | 200.0       |
| 287      | 0.000      | 200.0       | 0.000      | 200.0       | 20.0       | 200.0       |
| 288      | 1.774      | 1.2         | 1.744      | 1.5         | 1.780      | 3.9         |
| 289      | 0.000      | 200.0       | 0.000      | 200.0       | 20.0       | 200.0       |
| 290      | 1.864      | 1.2         | 1.834      | 1.5         | 1.870      | 3.9         |
| 291      | 1.792      | 1.1         | 1.763      | 1.4         | 1.790      | 2.8         |
| 292      | 1.852      | 1.2         | 1.822      | 1.4         | 1.860      | 3.2         |
| 293      | 1.910      | 1.7         | 1.878      | 1.3         | 1.930      | 3.2         |
| 295      | 1.870      | 1.4         | 1.838      | 1.4         | 1.870      | 3.8         |
| 24       | 1.920      | 1.5         | 1.889      | 1.4         | 1.940      | 2.8         |
| 37       | 1.840      | 5.2         | 1.693      | 32.7        | 0.860      | 47.5        |
| 38       | 0.000      | 200.0       | 0.000      | 200.0       | 20.0       | 200.0       |
| 42       | 1.910      | 1.7         | 1.876      | 1.5         | 1.920      | 4.4         |
| 47       | 1.830      | 26.6        | 1.648      | 227.0       | 20.0       | 200.0       |

TABLE 23. LOW TEMPERATURE PARAMETER  
MEASUREMENTS AT 125°C

| Specimen | 120 Hz     |             | 1 kHz      |             | 10 kHz     |             |
|----------|------------|-------------|------------|-------------|------------|-------------|
|          | C, $\mu$ F | DF, percent | C, $\mu$ F | DF, percent | C, $\mu$ F | DF, percent |
| 93       | 0.0912     | 2.7         | 0.0876     | 3.1         | 0.0848     | 3.0         |
| 94       | 0.0943     | 2.7         | 0.0904     | 3.1         | 0.0876     | 3.0         |
| 95       | 0.0000     | 200.0       | 0.0000     | 200.0       | 0.0000     | 0.0         |
| 96       | 0.0970     | 0.0         | 2000.0     | 2000.0      | 2.0000     | 200.0       |
| 97       | 0.0000     | 200.0       | 0.0000     | 2000.0      | 0.0359     | 0.0         |
| 98       | 0.0780     | 11.7        | 0.0742     | 4.9         | 34.7000    | 461.0       |
| 99       | 0.0598     | 3.1         | 0.0575     | 3.4         | 0.0556     | 7.3         |
| 100      | 0.0915     | 2.7         | 0.0877     | 3.2         | 10.2600    | 23.2        |
| 101      | 0.0909     | 2.4         | 0.0874     | 2.9         | 0.0847     | 3.1         |
| 102      | 0.0849     | 2.8         | 0.0813     | 3.2         | 0.0787     | 3.1         |
| 103      | 0.0882     | 2.6         | 0.0846     | 4.9         | 0.0818     | 23.3        |
| 104      | 0.0000     | 200.0       | 0.0000     | 200.0       | 0.0000     | 0.0         |
| 105      | 0.0768     | 2.0         | 0.0740     | 2.7         | 0.0719     | 3.2         |
| 106      | 0.0855     | 2.4         | 0.0822     | 2.9         | 0.0797     | 3.1         |
| 10       | 0.1061     | 6.4         | 0.1006     | 3.9         | 0.0970     | 3.6         |
| 14       | 0.0000     | 200.0       | 0.0000     | 200.0       | 0.0000     | 0.0         |
| 18       | 0.1018     | 2.6         | 0.0976     | 3.6         | 0.0945     | 7.8         |
| 19       | 0.0969     | 2.5         | 0.0929     | 3.2         | 0.0899     | 3.9         |
| 21       | 0.1045     | 3.4         | 0.0996     | 3.8         | 0.0961     | 6.7         |
| 23       | 0.0806     | 675.0       | 0.0695     | 73.5        | 0.0627     | 12.9        |
| 278      | 1.990      | 3.2         | 1.900      | 3.9         | 1.870      | 6.9         |
| 279      | 2.040      | 3.2         | 1.940      | 4.9         | 1.880      | 15.2        |
| 280      | 2.010      | 3.0         | 1.920      | 3.5         | 1.900      | 4.2         |
| 283      | 1.990      | 3.3         | 1.900      | 6.7         | 1.650      | 20.0        |
| 284      | 2.010      | 2.8         | 1.920      | 3.4         | 1.910      | 3.9         |
| 285      | 1.970      | 3.0         | 1.880      | 3.5         | 1.860      | 4.4         |
| 286      | 0.000      | 200.0       | 0.000      | 200.0       | 20.0       | 200.0       |
| 287      | 0.000      | 200.0       | 0.000      | 200.0       | 20.0       | 200.0       |
| 288      | 1.970      | 3.0         | 1.879      | 3.6         | 1.870      | 4.7         |
| 289      | 0.000      | 200.0       | 0.000      | 200.0       | 20.0       | 200.0       |
| 290      | 2.090      | 3.0         | 1.990      | 4.1         | 1.960      | 9.2         |
| 291      | 2.000      | 2.9         | 1.910      | 3.7         | 1.880      | 6.7         |
| 292      | 2.080      | 3.2         | 1.980      | 3.8         | 1.950      | 6.2         |
| 293      | 2.150      | 3.1         | 2.040      | 3.8         | 2.030      | 6.2         |
| 295      | 2.110      | 3.2         | 2.000      | 3.9         | 1.960      | 5.6         |
| 24       | 2.140      | 3.2         | 2.030      | 3.5         | 2.020      | 3.7         |
| 37       | 2.030      | 8.3         | 1.730      | 45.0        | 0.810      | 54.0        |
| 38       | 0.000      | 200.0       | 0.000      | 200.0       | 20.0       | 200.0       |
| 42       | 2.130      | 3.4         | 2.020      | 3.9         | 2.010      | 6.3         |
| 47       | 2.020      | 22.8        | 1.770      | 274.0       | 0.990      | 148.2       |

TABLE 24. LOW TEMPERATURE INSULATION  
RESISTANCE OF 0.1  $\mu$ F CAPACITORS

| Specimen                 | -55°C<br>G $\Omega$ | -3°C<br>G $\Omega$ | 25°C<br>G $\Omega$ | 125°C<br>G $\Omega$ |
|--------------------------|---------------------|--------------------|--------------------|---------------------|
| 93                       | 54.8975             | 11.1761            | 11.0880            | 0.0056              |
| 94                       | 57.0414             | 9.7154             | 12.5098            | 0.0119              |
| 95*                      |                     |                    |                    |                     |
| 96                       | 58.2830             | 0.4072             | 20.2966            | 0.0339              |
| 97*                      |                     |                    |                    |                     |
| 98                       | 73.2523             | 32.1237            | 1.8645             | 0.0101              |
| 99                       | 92.6923             | 191.2000           | 4.3192             | 0.0081              |
| 100                      | 59.6535             | 11.3190            | 21.9423            | 0.0270              |
| 101                      | 57.1090             | 28.7778            | 15.7566            | 0.0186              |
| 102                      | 64.6113             | 10.2641            | 8.3800             | 0.0106              |
| 103                      | 63.2546             | 208.7336           | 22.1145            | 0.0287              |
| 104*                     |                     |                    |                    |                     |
| 105                      | 13.7675             | 7.1397             | 3.9950             | 0.0439              |
| 106                      | 43.2675             | 221.2963           | 16.6089            | 0.0375              |
| 10                       | 55.0857             | 69.1751            | 4.3466             | 0.0070              |
| 14*                      |                     |                    |                    |                     |
| 18                       | 39.3469             | 5.4591             | 1.4550             | 0.0288              |
| 19                       | 24.1968             | 2.6423             | 1.8843             | 0.0235              |
| 21                       | 0.0010              | 0.0000             | 0.0010             | 0.0010              |
| 23                       | 0.0010              | 0.0010             | 0.0010             | 0.0010              |
| *Failed low temperature. |                     |                    |                    |                     |



TABLE 25. LOW TEMPERATURE INSULATION  
RESISTANCE OF 2  $\mu$ F CAPACITORS

| Specimen                 | -55°C<br>GΩ | -3°C<br>GΩ | 25°C<br>GΩ | 125°C<br>GΩ |
|--------------------------|-------------|------------|------------|-------------|
| 278                      | 6.1613      | -7.2397    | 0.9565     | 0.0882      |
| 279                      | 3.6766      | -1.1103    | 52.1786    | 0.7535      |
| 280                      | 4.3502      | 0.9004     | 1.4415     | 0.0146      |
| 283                      | 4.8442      | 10.0056    | 1.3432     | 0.0172      |
| 284                      | 5.2052      | -7.8819    | 0.8888     | 0.0018      |
| 285                      | 5.5017      | 1.0127     | 1.0317     | 0.0019      |
| 286*                     |             |            |            |             |
| 287*                     |             |            |            |             |
| 288*                     |             |            |            |             |
| 289*                     |             |            |            |             |
| 290                      | 3.4404      | -4.1410    | 1.4449     | 0.0019      |
| 291                      | 4.1445      | -61.1183   | 0.6551     | 0.0148      |
| 292                      | 3.8529      | -12.8591   | 1.0468     | 0.0138      |
| 293                      | 4.2730      | 2.4177     | 0.4819     | 0.0018      |
| 295                      | 4.9034      | 11.1006    | 1.4163     | 0.0021      |
| 24                       | 3.2027      | 0.2007     | 0.5359     | 0.0016      |
| 37                       | 367.9389    | -6.7939    | 2.6685     | 0.0024      |
| 38*                      |             |            |            |             |
| 42                       | 6.4490      | 4.7692     | 1.3643     | 0.0020      |
| 47                       | 16.1204     | -0.1897    | 1.2179     | 0.0021      |
| *Failed low temperature. |             |            |            |             |

TABLE 26. LOW TEMPERATURE TEST RESULTS

| Capacitor   | Initial<br>Quantity | Number of Survivors/Failures |       |      |       |
|-------------|---------------------|------------------------------|-------|------|-------|
|             |                     | -3°C                         | -55°C | 25°C | 125°C |
| 0.1 $\mu$ F | 20                  | 16/4                         | 14/2  | 13/1 | 13/0  |
| 2 $\mu$ F   | 20                  | 16/4                         | 15/1  | 14/1 | 14/0  |

## VII. LIFE TESTS

### REQUIREMENTS

The life testing prescribed in the statement of work consisted of:

1. 120 capacitors, 60 each type
2. 500 VDC + 20 VAC at 10 kHz
3. 10,000 hours at elevated temperature.

The required temperatures were 125, 105 and 85°C. Six capacitors of each type were operated at 25°C as controls. The dissipation factor, capacitance, and the insulation resistance of each capacitor were measured at the life test temperature initially and at regular intervals throughout the test. The capacitance and DF measurements were made at 120 Hz, 1 kHz, and 10 kHz.

Shortly after the start of the life test, due to excessive losses, NASA agreed to reduce the upper temperature limit and the AC voltage. Consequently, the upper temperature limit was changed from 125 to 105°C, making the test temperatures 105, 85 and 60°C. Also, the applied voltage was changed from 500 VDC plus 20 VAC to 500 VDC plus 10 VAC at 10 kHz to reduce the power dissipation.

### CIRCUITRY

The design of the life test circuit requires one main inverter and several secondary inverters. In Figure 30, the main inverter and one secondary inverter are shown; the remaining inverters attach to the multiple secondary windings on  $T_1$ . This inverter design produces 10 kHz sine waves across the test components. If a component fails, either open or short, the interlock relays deactivate the system and turn on an alarm light. Manual reset is required for startup.

### TEST DATA

Capacitance, DF, and insulation resistance were measured after 1000 hours, 2500 hours, and 5000 hours at each temperature. The data

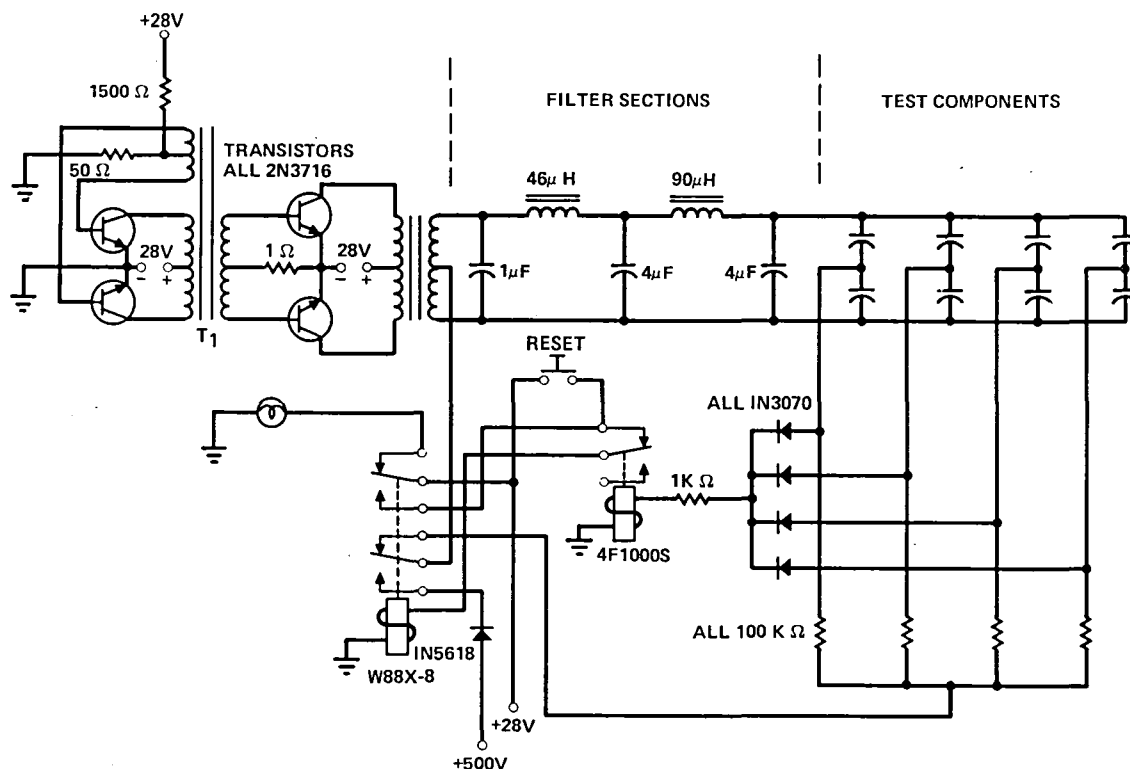


Figure 30. Life test circuit.

for 60°C are presented in Tables 27 through 29. The data for 85°C are shown in Tables 30 through 32. The data for 105°C are given in Tables 33 through 35. The data for 25°C are shown in Tables 36 through 38. The above data are for the 0.1  $\mu\text{F}$  capacitors. None of the 2  $\mu\text{F}$  capacitors survived the original test conditions.

## DISCUSSION OF RESULTS

The life test conditions prescribed originally were 500 VDC plus 20 VAC at the extreme temperature of 125°C. Initial thermocouple measurements of the case temperature of the 0.1  $\mu\text{F}$  capacitors at room ambient showed excessive heating. The AC voltage was reduced to 10 V and the capacitors tested again. Some additional failures were caused by infant mortality. The upper temperature limit was reduced to 105°C, and the remaining components put on test at 60°C, 85°C, and 105°C.

Concurrently, the initial measurements of the 2  $\mu$ F capacitors were made at 500 VDC plus 10 VAC. Several failures occurred. The remaining components were put on life test at 60, 85 and 105°C. The capacitors at 85°C all failed within 2 to 4 hours. At 105°C, the lifetime was about 30 minutes. Those operated at 60°C also failed within a short time. All of the 2  $\mu$ F capacitors failed catastrophically.

During the life test, parameter measurements at each temperature were made after 1000, 2500, and 5000 hours. Many failures occurred during the progress of the life test. The results are summarized in Table 39.

Since no previous screening had been made to eliminate the weak parts, the initial failures were attributed to infant mortality. In addition, some degradation has occurred since some of the survivors at 105 and 85°C have acquired a high DF, after 1000 hours.

TABLE 27. PARAMETER MEASUREMENTS  
AFTER 1000 HOURS AT 60°C

| Specimen                      | 120 Hz     |                | 1 kHz      |                | 10 kHz     |                | 1R         |
|-------------------------------|------------|----------------|------------|----------------|------------|----------------|------------|
|                               | C, $\mu$ F | DF,<br>percent | C, $\mu$ F | DF,<br>percent | C, $\mu$ F | DF,<br>percent | G $\Omega$ |
| 57                            | 0.0547     | 2.1            | 0.0533     | 1.4            | 0.0532     | 1.5            | 19.8473    |
| 58                            | 0.0436     | 169.2          | 0.0427     | 19.6           | 0.0424     | 10.2           | 0.0010     |
| 59                            | 0.0550     | 2.2            | 0.0536     | 1.5            | 0.0533     | 1.8            | 0.0030     |
| 60*                           |            |                |            |                |            |                |            |
| 62                            | 0.0518     | 2.5            | 0.0503     | 1.9            | 0.0499     | 4.0            | 1.5476     |
| 63                            | 0.0645     | 2.4            | 0.0627     | 1.7            | 0.0623     | 2.1            | 1.5589     |
| 67*                           |            |                |            |                |            |                |            |
| 4?                            | 0.0783     | 2.4            | 0.0761     | 1.7            | 0.0758     | 1.8            | 1.1215     |
| 5?*                           | 0.0513     | 1020.0         | 0.0485     | 118.1          | 0.0486     | 14.1           |            |
| ?                             | 0.0511     | 71.1           | 0.0017     | 663.00         | 0.0569     | 20000.0        | 3.8117     |
| 148                           | 0.0887     | 2.9            | 0.0857     | 2.0            | 0.0850     | 2.0            | 0.4750     |
| 149*                          |            |                |            |                |            |                |            |
| 29                            | 0.0592     | 2.2            | 0.0577     | 1.6            | 0.0574     | 1.9            | 3.3088     |
| 32                            | 0.0773     | 2.4            | 0.0752     | 1.7            | 0.0748     | 1.6            | 2.7460     |
| 35                            | 0.0623     | 2.1            | 0.0607     | 1.5            | 0.0605     | 1.6            | 2.7460     |
| 36                            | 0.0809     | 2.3            | 0.0787     | 1.6            | 0.0784     | 1.6            | 2.0879     |
| 37                            | 0.0596     | 2.3            | 0.0579     | 1.6            | 0.0577     | 1.6            | 3.0363     |
| 39                            | 0.0695     | 2.2            | 0.0677     | 1.5            | 0.0674     | 1.6            | 13.8803    |
| * Shorted. Removed from test. |            |                |            |                |            |                |            |

TABLE 28. PARAMETER MEASUREMENTS  
AFTER 2500 HOURS AT 60°C

| Specimen           | 120 Hz     |                | 1 kHz      |                | 10 kHz     |                | 1R         |
|--------------------|------------|----------------|------------|----------------|------------|----------------|------------|
|                    | C, $\mu$ F | DF,<br>percent | C, $\mu$ F | DF,<br>percent | C, $\mu$ F | DF,<br>percent | G $\Omega$ |
| 57                 | 0.0553     | 2.0            | 0.0540     | 1.4            | 0.0538     | 1.5            | 22.1       |
| 58                 | 0.0000     | 200.0          | 0.0000     | 75.1           | 0.0000     | 13.6           | 0.0        |
| 59*                |            |                |            |                |            |                |            |
| 60*                |            |                |            |                |            |                |            |
| 62                 | 0.01441    | 2.2            | 0.0141     | 1.9            | 0.0137     | 4.9            | 16.91      |
| 63                 | 0.00119    | 137.0          | 0.0009     | 18.3           | 0.0009     | 3.3            | 3.85       |
| 67*                |            |                |            |                |            |                |            |
| 4?                 | 0.0756     | 2.0            | 0.0738     | 1.5            | 0.0735     | 1.9            | 1.71       |
| 5?                 |            |                |            |                |            |                |            |
| ?                  | 0.0760     | 3.2            | 0.0723     | 16.4           | 0.0737     | 150.7          | 4.22       |
| 148                | 0.0027     | 3.6            | 0.0026     | 2.2            | 0.0026     | 2.0            | 14.50      |
| 149*               |            |                |            |                |            |                |            |
| 29*                |            |                |            |                |            |                |            |
| 32                 | 0.0749     | 2.2            | 0.0729     | 1.6            | 0.0725     | 1.7            | 2.70       |
| 35                 | 0.0627     | 2.0            | 0.0612     | 1.4            | 0.0610     | 1.7            | 16.77      |
| 36                 | 0.0563     | 2.0            | 0.0550     | 1.5            | 0.0547     | 2.2            | 5.29       |
| 37                 | 0.0589     | 2.1            | 0.0574     | 1.5            | 0.0572     | 1.7            | 2.67       |
| 39                 | 0.0697     | 1.9            | 0.0681     | 1.4            | 0.0678     | 1.6            | 9.45       |
| Removed from test. |            |                |            |                |            |                |            |

TABLE 29. PARAMETER MEASUREMENTS  
AFTER 5000 HOURS AT 60°C

| Specimen            | 120 Hz     |                | 1 kHz      |                | 10 kHz     |                | 1R         |
|---------------------|------------|----------------|------------|----------------|------------|----------------|------------|
|                     | C, $\mu$ F | DF,<br>percent | C, $\mu$ F | DF,<br>percent | C, $\mu$ F | DF,<br>percent | G $\Omega$ |
| 57                  | 0.0550     | 2.1            | 0.0535     | 1.5            | 0.0533     | 1.6            | 8166.67    |
| 58                  | 0.0000     | 200.0          | 0.0000     | 7.1            | 0.0000     | 0.0            | 0.49       |
| 59*                 |            |                |            |                |            |                |            |
| 60*                 |            |                |            |                |            |                |            |
| 62                  | 0.0005     | 3.1            | 0.0005     | 1.8            | 0.0005     | 1.4            | 85.51      |
| 63                  | 0.0008     | 3.1            | 0.0008     | 2.0            | 0.0008     | 1.6            | 3.45       |
| 67*                 |            |                |            |                |            |                |            |
| 4?                  | 0.0630     | 2.1            | 0.0614     | 1.6            | 0.0611     | 1.9            | 1.78       |
| 5? *                |            |                |            |                |            |                |            |
| ?                   | 0.0000     | 200.0          | 0.0000     | 200.0          | 0.0000     | 0.0            | 2.99       |
| 148                 | 0.0008     | 3.9            | 0.0008     | 2.1            | 0.0008     | 1.8            | 84.78      |
| 149*                |            |                |            |                |            |                |            |
| 29*                 |            |                |            |                |            |                |            |
| 32                  | 0.0256     | 2.2            | 0.0249     | 1.6            | 0.0248     | 1.8            | 20.77      |
| 35                  | 0.0625     | 2.1            | 0.0609     | 1.6            | 0.0606     | 1.7            | 38.61      |
| 36                  | 0.0005     | 3.0            | 0.0005     | 1.8            | 0.0005     | 1.4            | 245.00     |
| 37                  | 0.0580     | 2.3            | 0.0564     | 1.7            | 0.0561     | 1.8            | 3.68       |
| 39                  | 0.0695     | 2.3            | 0.0676     | 1.6            | 0.0672     | 1.7            | 22.43      |
| *Removed from test. |            |                |            |                |            |                |            |



TABLE 30. PARAMETER MEASUREMENTS  
AFTER 1000 HOURS AT 85°C

| Specimen            | 120 Hz     |                | 1 kHz      |                | 10 kHz     |                | 1R         |
|---------------------|------------|----------------|------------|----------------|------------|----------------|------------|
|                     | C, $\mu$ F | DF,<br>percent | C, $\mu$ F | DF,<br>percent | C, $\mu$ F | DF,<br>percent | G $\Omega$ |
| 164                 | 0.0885     | 194.0          | 0.0844     | 25.2           | 0.0815     | 16.9           | 0.0010     |
| 166                 | 0.0771     | 96.7           | 0.0715     | 27.8           | 0.0725     | 147.9          | 0.0010     |
| 167*                |            |                |            |                |            |                |            |
| 168                 | 0.0010     | 200.0          | 0.0004     | 2000.0         | 0.0009     | 0.0            | 4.7915     |
| 169                 | 0.0517     | 4.0            | 0.0492     | 3.4            | 0.0469     | 8.9            | 0.1994     |
| 170                 | 0.0970     | 153.7          | 0.0912     | 19.2           | 0.0896     | 4.0            | 0.0010     |
| 171*                |            |                |            |                |            |                |            |
| 172                 | 0.0002     | 9.5            | 0.0002     | 4.9            | 0.0002     | 2.1            | 3.5336     |
| 173*                |            |                |            |                |            |                |            |
| 174*                |            |                |            |                |            |                |            |
| 87*                 |            |                |            |                |            |                |            |
| 88*                 |            |                |            |                |            |                |            |
| 51                  | 0.0373     | 3.5            | 0.0357     | 2.5            | 0.0352     | 4.1            | 0.7445     |
| 52*                 |            |                |            |                |            |                |            |
| 54*                 |            |                |            |                |            |                |            |
| 55                  | 0.0728     | 2.9            | 0.0698     | 2.2            | 0.0692     | 2.3            | 2.3807     |
| 143*                |            |                |            |                |            |                |            |
| *Removed from test. |            |                |            |                |            |                |            |

TABLE 31. PARAMETER MEASUREMENTS  
AFTER 2500 HOURS AT 85°C

| Specimen            | 120 Hz     |                | 1 kHz      |                | 10 kHz     |                | 1R         |
|---------------------|------------|----------------|------------|----------------|------------|----------------|------------|
|                     | C, $\mu$ F | DF,<br>percent | C, $\mu$ F | DF,<br>percent | C, $\mu$ F | DF,<br>percent | G $\Omega$ |
| 164                 | 0.0913     | 108.4          | 0.0844     | 16.6           | 0.0812     | 18.7           | 0.0010     |
| 166                 | 0.0763     | 92.1           | 0.0682     | 35.6           | 0.0715     | 229.0          | 0.0010     |
| 167*                |            |                |            |                |            |                |            |
| 168                 | 0.0004     | 6.1            | 0.0004     | 3.7            | 0.0004     | 2.0            | 7.9441     |
| 169*                |            |                |            |                |            |                |            |
| 170                 | 0.0965     | 43.4           | 0.0906     | 7.4            | 0.0891     | 2.9            | 0.0010     |
| 171*                |            |                |            |                |            |                |            |
| 172                 | 0.0001     | 10.6           | 0.0001     | 5.3            | 0.0001     | 2.1            | 7.5363     |
| 173*                |            |                |            |                |            |                |            |
| 174*                |            |                |            |                |            |                |            |
| 87*                 |            |                |            |                |            |                |            |
| 88*                 |            |                |            |                |            |                |            |
| 51                  | 0.0005     | 5.0            | 0.0004     | 3.3            | 0.0004     | 1.9            | 11.6779    |
| 52                  | 0.0795     | 103.3          | 0.0764     | 12.9           | 0.0758     | 0.6            | 0.0010     |
| 54*                 |            |                |            |                |            |                |            |
| 55                  | 0.0690     | 3.0            | 0.0661     | 2.2            | 0.0655     | 1.9            | 4.6667     |
| 143*                |            |                |            |                |            |                |            |
| * Removed from test |            |                |            |                |            |                |            |

TABLE 32. PARAMETER MEASUREMENTS  
AFTER 5000 HOURS AT 85°C

| Specimen            | 120 Hz     |             | 1 kHz      |             | 10 kHz     |             | 1R         |
|---------------------|------------|-------------|------------|-------------|------------|-------------|------------|
|                     | C, $\mu$ F | DF, percent | C, $\mu$ F | DF, percent | C, $\mu$ F | DF, percent | G $\Omega$ |
| 164                 | 0.0875     | 186.5       | 0.0826     | 23.3        | 0.0816     | 13.0        | 0.2687     |
| 166                 | 0.0763     | 127.4       | 0.0717     | 26.6        | 0.0722     | 106.4       | 0.3891     |
| 167*                |            |             |            |             |            |             |            |
| 168                 | 0.0003     | 3.9         | 0.0003     | 2.7         | 0.0003     | 1.3         | 641.0256   |
| 169*                |            |             |            |             |            |             |            |
| 170                 | 0.0953     | 64.8        | 0.0897     | 9.5         | 0.0885     | 3.1         | 0.0010     |
| 171*                |            |             |            |             |            |             |            |
| 172                 | 0.0001     | 200.0       | 0.0001     | 5.1         | 0.0000     | 1.8         | 3.3135     |
| 173*                |            |             |            |             |            |             |            |
| 174*                |            |             |            |             |            |             |            |
| 87*                 |            |             |            |             |            |             |            |
| 88*                 |            |             |            |             |            |             |            |
| 51                  | 0.0003     | 3.6         | 0.0003     | 2.5         | 0.0003     | 1.6         | 65.8762    |
| 52                  | 0.0791     | 227.0       | 0.0759     | 25.8        | 0.0755     | 4.0         | 0.0010     |
| 54*                 |            |             |            |             |            |             |            |
| 55                  | 0.0627     | 3.2         | 0.0599     | 2.3         | 0.0593     | 1.9         | 9.3284     |
| 143*                |            |             |            |             |            |             |            |
| * Removed from test |            |             |            |             |            |             |            |

TABLE 33. PARAMETER MEASUREMENTS  
AFTER 1000 HOURS AT 105°C

| Specimen            | 120 Hz     |             | 1 kHz      |             | 10 kHz     |             | 1R         |
|---------------------|------------|-------------|------------|-------------|------------|-------------|------------|
|                     | C, $\mu$ F | DF, percent | C, $\mu$ F | DF, percent | C, $\mu$ F | DF, percent | G $\Omega$ |
| 150*                |            |             |            |             |            |             |            |
| 151                 | 0.0751     | 3.5         | 0.0715     | 2.9         | 0.0704     | 3.5         | 0.6639     |
| 152                 | 0.0000     | 200.0       | 0.0012     | 200.0       | 0.2000     | 200.0       |            |
| 153*                |            |             |            |             |            |             |            |
| 154                 | 0.0976     | 201.0       | 0.0882     | 28.1        | 0.0841     | 16.1        | 0.0010     |
| 156*                |            |             |            |             |            |             |            |
| 157*                |            |             |            |             |            |             |            |
| 158                 | 0.0662     | 162.7       | 0.0631     | 26.3        | 0.0623     | 55.1        | 0.0010     |
| 159*                |            |             |            |             |            |             |            |
| 161*                |            |             |            |             |            |             |            |
| 162*                |            |             |            |             |            |             |            |
| 163                 | 0.0399     | 8.9         | 0.0299     | 53.4        | 0.0018     | 429.0       | 0.0011     |
| 41                  | 0.0010     | 14.2        | 0.0009     | 7.6         | 0.0009     | 3.1         | 3.2224     |
| 44*                 |            |             |            |             |            |             |            |
| 45*                 |            |             |            |             |            |             |            |
| 46                  | 0.0697     | 2.9         | 0.0665     | 2.8         | 0.0654     | 2.0         | 1.1268     |
| 48*                 |            |             |            |             |            |             |            |
| 49                  | 0.0000     | 200.0       | 0.0000     | 200.0       | 0.0000     | 0.0         | 388.97     |
| * Removed from test |            |             |            |             |            |             |            |

TABLE 34. PARAMETER MEASUREMENTS  
AFTER 2500 HOURS AT 105°C

| Specimen            | 120 Hz     |                | 1 kHz      |                | 10 kHz     |                | 1R         |
|---------------------|------------|----------------|------------|----------------|------------|----------------|------------|
|                     | C, $\mu$ F | DF,<br>percent | C, $\mu$ F | DF,<br>percent | C, $\mu$ F | DF,<br>percent | G $\Omega$ |
| 150*                |            |                |            |                |            |                |            |
| 151*                |            |                |            |                |            |                |            |
| 152                 | 200.0      | 2000.0         | 20.0       | 200.0          | 2.0000     | 200.0          | 0.0010     |
| 153*                |            |                |            |                |            |                |            |
| 154                 | 0.0015     | 2000.0         | 0.0006     | 2000.0         | 0.0003     | 838.0          | 0.0010     |
| 156*                |            |                |            |                |            |                |            |
| 157*                |            |                |            |                |            |                |            |
| 158                 | 0.0544     | 36.4           | 0.0371     | 53.3           | 0.0037     | 300.0          | 0.0010     |
| 159*                |            |                |            |                |            |                |            |
| 161*                |            |                |            |                |            |                |            |
| 162*                |            |                |            |                |            |                |            |
| 163*                |            |                |            |                |            |                |            |
| 41                  | 0.0001     | 2000.0         | 0.0001     | 8.8            | 0.0001     | 3.7            | 0.7188     |
| 44*                 |            |                |            |                |            |                |            |
| 45*                 |            |                |            |                |            |                |            |
| 46                  | 0.0538     | 3.8            | 0.0506     | 3.5            | 0.0496     | 2.4            | 1.0988     |
| 48*                 |            |                |            |                |            |                |            |
| 49                  | 0.0000     | 200.0          | 0.0000     | 200.0          | 0.0000     | 0.0            | 9.4931     |
| * Removed from test |            |                |            |                |            |                |            |

TABLE 35. PARAMETER MEASUREMENTS  
AFTER 5000 HOURS AT 105° C

| Specimen            | 120 Hz     |             | 1 kHz      |             | 10 kHz     |             | 1R         |
|---------------------|------------|-------------|------------|-------------|------------|-------------|------------|
|                     | C, $\mu$ F | DF, percent | C, $\mu$ F | DF, percent | C, $\mu$ F | DF, percent | G $\Omega$ |
| 150*                |            |             |            |             |            |             |            |
| 151*                |            |             |            |             |            |             |            |
| 152                 | 200.0      | 200.0       | 20.0       | 200.0       | 2.0000     | 200.0       | 0.0940     |
| 153*                |            |             |            |             |            |             |            |
| 154                 | 0.0005     | 215.0       | 0.0003     | 82.5        | 0.0001     | 88.1        | 0.0011     |
| 156*                |            |             |            |             |            |             |            |
| 157*                |            |             |            |             |            |             |            |
| 158                 | 0.0558     | 37.2        | 0.0393     | 44.4        | 0.0003     | 800.0       | 0.0011     |
| 159*                |            |             |            |             |            |             |            |
| 161*                |            |             |            |             |            |             |            |
| 162*                |            |             |            |             |            |             |            |
| 163*                |            |             |            |             |            |             |            |
| 41*                 |            |             |            |             |            |             |            |
| 44*                 |            |             |            |             |            |             |            |
| 45*                 |            |             |            |             |            |             |            |
| 46                  | 0.0522     | 4.1         | 0.0496     | 2.9         | 0.0489     | 2.2         | 0.3401     |
| 48*                 |            |             |            |             |            |             |            |
| 49*                 |            |             |            |             |            |             |            |
| * Removed from test |            |             |            |             |            |             |            |

TABLE 36. PARAMETER MEASUREMENTS  
AFTER 1000 HOURS AT 25° C

| Specimen            | 120 Hz     |                | 1 kHz      |                | 10 kHz     |                | 1R         |
|---------------------|------------|----------------|------------|----------------|------------|----------------|------------|
|                     | C, $\mu$ F | DF,<br>percent | C, $\mu$ F | DF,<br>percent | C, $\mu$ F | DF,<br>percent | G $\Omega$ |
| 89                  | 0.0738     | 1.1            | 0.725      | 1.4            | 0.0720     | 2.7            | 55.7562    |
| 90*                 |            |                |            |                |            |                |            |
| 91                  | 0.0611     | 1.2            | 0.0600     | 1.9            | 0.0594     | 8.7            | 67.9505    |
| 145*                |            |                |            |                |            |                |            |
| 147                 | 0.0762     | 1.2            | 0.0748     | 1.4            | 0.742      | 2.8            | 3.8117     |
| 273                 | 0.0003     | 43.5           | 0.0002     | 50.2           | 0.0001     | 44.5           |            |
| 274                 | 1.7170     | 1.1            | 1.6870     | 1.4            | 1.7150     | 3.5            |            |
| 276                 | 1.7330     | 5.6            | 1.7050     | 1.9            | 1.7370     | 5.6            |            |
| 277                 | 0.0055     | 132.9          | 0.0032     | 48.0           | 0.0022     | 28.8           |            |
| * Removed from test |            |                |            |                |            |                |            |

TABLE 37. PARAMETER MEASUREMENTS  
AFTER 2500 HOURS AT 25°C

| Specimen            | 120 Hz     |                | 1 kHz      |                | 10 kHz     |                | 1R         |
|---------------------|------------|----------------|------------|----------------|------------|----------------|------------|
|                     | C, $\mu$ F | DF,<br>percent | C, $\mu$ F | DF,<br>percent | C, $\mu$ F | DF,<br>percent | G $\Omega$ |
| 89                  | 0.0734     | 1.1            | 0.0722     | 1.3            | 0.0719     | 2.5            | 47.7673    |
| 90*                 |            |                |            |                |            |                |            |
| 91                  | 0.0606     | 1.2            | 0.0596     | 1.9            | 0.0590     | 8.4            | 73.5160    |
| 145*                |            |                |            |                |            |                |            |
| 147                 | 0.0755     |                | 0.0742     | 1.3            | 0.0738     | 2.6            | 4.6667     |
| 273                 | 0.0003     | 55.2           | 0.0002     | 61.6           | 20.0000    | 200.0          |            |
| 274                 | 12.880     | 2000.0         | 0.1750     | 0.0            | 1.6700     | 23.0           |            |
| 276                 | 1.7300     | 3.6            | 1.7030     | 1.8            | 1.7400     | 5.6            |            |
| 277                 | 0.0039     | 59.6           | 0.0026     | 29.7           | 20.0000    | 200.0          |            |
| * Removed from test |            |                |            |                |            |                |            |



TABLE 38. PARAMETER MEASUREMENTS  
AFTER 5000 HOURS AT 25° C

| Specimen            | 120 Hz     |                | 1 kHz      |                | 10 kHz     |                | 1R         |
|---------------------|------------|----------------|------------|----------------|------------|----------------|------------|
|                     | C, $\mu$ F | DF,<br>percent | C, $\mu$ F | DF,<br>percent | C, $\mu$ F | DF,<br>percent | G $\Omega$ |
| 89                  | 0.0741     | 1.3            | 0.0726     | 1.6            | 0.0720     | 3.1            | 25000.0000 |
| 90*                 |            |                |            |                |            |                |            |
| 91                  | 0.0610     | 1.3            | 0.0598     | 2.2            | 0.0590     | 9.3            | 0.1710     |
| 145*                |            |                |            |                |            |                |            |
| 147                 | 0.0755     | 1.3            | 0.0740     | 1.6            | 0.0733     | 3.2            | 5.3533     |
| 273                 | 200.0      | 200.0          | 0.0002     | 185.0          | 20.0000    | 200.0          |            |
| 274                 | 1.7000     | 1.5            | 1.6680     | 1.4            | 1.7000     | 3.6            |            |
| 276                 | 1.7200     | 5.5            | 1.6880     | 2.0            | 1.7100     | 5.8            |            |
| 277                 | 0.0037     | 45.6           | 0.0025     | 27.9           | 20.0000    | 200.0          |            |
| * Removed from test |            |                |            |                |            |                |            |

TABLE 39. LIFE TEST RESULTS FOR 0.1  $\mu$ F CAPACITORS

| Temperature | Initial Quantity | Initial IR Failures | Number of Survivors/Failures |            |            |            |
|-------------|------------------|---------------------|------------------------------|------------|------------|------------|
|             |                  |                     | 0 hours                      | 1000 hours | 2500 hours | 5000 hours |
| 105°C       | 18               | 5                   | 13                           | 5/8        | 2/3        | 2/0        |
| 85°C        | 17               | 3                   | 12                           | 6/6        | 4/2        | 4/0        |
| 60°C        | 18               | 2                   | 16                           | 12/4       | 9/3        | 6/3        |
| 25°C        | 6                | 1                   | 5                            | 3/2        | 3/0        | 3/0        |

## VIII. THERMAL CYCLING

### MEASUREMENTS

Fifty capacitors, 25 of each type, were subjected to five thermal cycles from  $-55$  to  $125^{\circ}\text{C}$ . The dwell time at each temperature limit was 30 minutes. At the conclusion of the five cycles, the insulation resistance, capacitance, and dissipation factor were measured. The test data are presented in Table 40.

### DISCUSSION OF RESULTS

During initial parameter measurements, one  $0.1\ \mu\text{F}$  capacitor was open and one  $2\ \mu\text{F}$  capacitor was shorted. During initial IR measurements, three capacitors of each type failed catastrophically. No failures were caused by thermal cycling.

TABLE 40. PARAMETER MEASUREMENTS AFTER  
THERMAL CYCLING

| Specimen | 120 Hz     |             | 1 kHz      |             | 10 kHz     |             | 1R         |
|----------|------------|-------------|------------|-------------|------------|-------------|------------|
|          | C, $\mu$ F | DF, percent | C, $\mu$ F | DF, percent | C, $\mu$ F | DF, percent | G $\Omega$ |
| 65       | 0.0713     | 0.9         | 0.0703     | 1.1         | 0.0701     | 2.4         | 21.7778    |
| 66       | 0.0407     | 1.0         | 0.0401     | 1.5         | 0.0399     | 6.6         | 29.9694    |
| 67*      |            |             |            |             |            |             |            |
| 68*      |            |             |            |             |            |             |            |
| 70       | 0.0649     | 0.9         | 0.0640     | 1.0         | 0.0638     | 2.4         | 2.0887     |
| 71       | 0.0688     | 0.9         | 0.0678     | 1.0         | 0.0577     | 2.4         | 0.2530     |
| 72       | 0.0662     | 0.9         | 0.0653     | 1.0         | 0.0652     | 2.3         | 24.3418    |
| 73       | 0.0558     | 0.9         | 0.0550     | 1.0         | 0.0549     | 3.5         | 25.9122    |
| 74       | 0.0429     | 1.0         | 0.0423     | 2.0         | 0.0417     | 11.8        | 0.0010     |
| 75       | 0.0638     | 0.9         | 0.0629     | 1.0         | 0.0628     | 2.6         | 15.4916    |
| 76       | 0.0585     | 1.1         | 0.0576     | 2.0         | 0.0570     | 10.0        | 0.0269     |
| 77*      |            |             |            |             |            |             |            |
| 78       | 0.0832     | 1.0         | 0.0820     | 1.0         | 0.0819     | 2.4         | 18.5185    |
| 79       | 0.0450     | 1.1         | 0.0442     | 3.0         | 0.0432     | 15.4        |            |
| 80       | 0.0663     | 1.0         | 0.0653     | 1.0         | 0.0652     | 2.4         | 20.3912    |
| 81       | 0.0849     | 1.1         | 0.0835     | 1.0         | 0.0833     | 2.5         | 15.7001    |
| 82       | 0.0750     | 1.0         | 0.0739     | 1.0         | 0.0737     | 2.4         | 16.1761    |
| 83       | 0.0602     | 1.0         | 0.0593     | 2.0         | 0.0590     | 4.6         | 25.4413    |
| 85       | 0.0587     | 1.0         | 0.0579     | 2.0         | 0.0575     | 7.9         |            |
| 86       | 0.0698     | 1.0         | 0.0687     | 1.0         | 0.0585     | 2.5         | 24.1737    |
| 92       | 1.768      | 1.0         | 1.738      | 1.0         | 1.770      | 3.3         | 0.0010     |
| 98       | 1.720      | 1.5         | 1.689      | 2.0         | 1.710      | 3.3         | 2.1879     |
| 99       | 1.666      | 1.0         | 1.639      | 2.0         | 1.670      | 3.1         | 0.0185     |
| 100      | 1.770      | 1.5         | 1.742      | 2.0         | 1.770      | 3.9         | 2.1909     |
| 101      | 1.740      | 1.5         | 1.707      | 2.0         | 1.730      | 4.7         | 2.1078     |
| 102      | 1.710      | 1.5         | 1.684      | 1.0         | 1.710      | 3.4         | 0.0139     |
| 107      | 1.740      | 1.4         | 1.710      | 2.0         | 1.740      | 3.8         | 2.0333     |
| 108      | 22.100     | 66.6        | 15.900     | 10.0        | 10.290     | 25.0        | 2.0107     |
| 110      | 1.695      | 1.1         | 1.666      | 1.0         | 1.690      | 4.1         | 2.3088     |
| 111      | 1.720      | 2.3         | 1.681      | 9.0         | 1.290      | 29.4        | 1.7666     |
| 112*     |            |             |            |             |            |             |            |
| 113*     |            |             |            |             |            |             |            |
| 114      | 1.717      | 1.1         | 1.688      | 2.0         | 1.720      | 3.3         | 2.1523     |
| 115      | 1.720      | 1.5         | 1.690      | 1.0         | 1.730      | 4.1         | 2.2618     |
| 118      | 1.750      | 1.6         | 1.723      | 2.0         | 1.750      | 3.5         | 2.4585     |
| 119      | 1.830      | 1.4         | 1.798      | 1.0         | 1.840      | 3.8         | 2.3197     |
| 121      | 1.722      | 1.0         | 1.693      | 1.0         | 1.720      | 4.0         | 2.5297     |
| 130      | 1.730      | 1.6         | 1.710      | 2.0         | 1.730      | 6.2         | 2.3982     |
| 140      | 1.730      | 1.6         | 1.700      | 2.0         | 1.730      | 3.8         | 0.2226     |
| 200      | 1.700      | 1.8         | 1.666      | 5.0         | 1.440      | 21.7        | 1.9072     |
| 107      | 0.0521     | 1.2         | 0.0513     | 3.0         | 0.0500     | 19.9        | 14.4714    |
| 108      | 0.0715     | 1.0         | 0.0704     | 1.1         | 0.0703     | 2.3         | 0.0010     |
| 110      | 0.0817     | 1.0         | 0.0804     | 1.1         | 0.0802     | 2.4         | 11.8443    |
| 111      | 0.1795     | 2.3         | 0.0505     | 0.0         | 1.243      | 9.4         | 24.5123    |
| 112      | 0.0592     | 1.1         | 0.0583     | 1.4         | 0.0580     | 4.8         | 14.0441    |
| 201      | 1.744      | 2.1         | 1.692      | 10.9        | 1.230      | 28.2        | 1.8407     |
| 202      | 1.695      | 1.1         | 1.667      | 1.5         | 1.690      | 5.0         | 0.0010     |
| 203      | 1.659      | 2.3         | 1.601      | 13.3        | 1.090      | 27.9        | 1.8068     |
| 205      | 1.742      | 1.1         | 1.720      | 1.4         | 1.740      | 3.6         | 0.0145     |

\*Removed from test.

## IX. VIBRATION

### MEASUREMENTS

Fifty capacitors, 25 of each type, were subjected to simple harmonic motion from 10 to 2000 Hz. The vibration amplitude was 0.06 inch or 20 g. During the test, 250 VDC was applied. Each component was vibrated in two axes, for a total 8-hour period. At the end of the test; the capacitance, dissipation factor, and insulation resistance were measured. The test data are given in Table 41.

### DISCUSSION OF RESULTS

During initial parameter measurements, one 0.1  $\mu\text{F}$  capacitor failed open and two 2.0  $\mu\text{F}$  capacitors had high DF. During initial IR measurements one 2  $\mu\text{F}$  capacitor failed. No failures were caused by vibration.

TABLE 41. PARAMETER MEASUREMENTS AFTER VIBRATION

| Specimen | 120 Hz           |             | 1 kHz            |             | 10 kHz           |             | 1R         |
|----------|------------------|-------------|------------------|-------------|------------------|-------------|------------|
|          | C, $\mu\text{F}$ | DF, percent | C, $\mu\text{F}$ | DF, percent | C, $\mu\text{F}$ | DF, percent | G $\Omega$ |
| 113      | 0.0477           | 2.6         | 0.0457           | 16.8        | 0.0477           | 149.6       | 13.0329    |
| 114      | 0.0764           | 1.3         | 0.0748           | 1.5         | 0.0743           | 2.6         | 18.3767    |
| 115      | 0.0635           | 1.0         | 0.0625           | 1.4         | 0.0623           | 4.4         | 6.1436     |
| 117      | 0.0738           | 1.1         | 0.0726           | 1.3         | 0.0723           | 2.8         | 26.2726    |
| 118      | 0.0808           | 1.1         | 0.0793           | 1.4         | 0.0789           | 3.1         | 15.2381    |
| 119      | 0.0553           | 1.1         | 0.0544           | 1.6         | 0.0540           | 6.8         | 23.5755    |
| 120      | 0.0708           | 1.0         | 0.0697           | 1.6         | 0.0694           | 7.2         | 39.1198    |
| 121      | 0.0817           | 1.1         | 0.0803           | 1.3         | 0.0801           | 2.7         | 3.3566     |
| 122      | 0.0704           | 1.1         | 0.0693           | 1.7         | 0.0688           | 7.8         | 18.8383    |
| 123      | 0.0806           | 1.0         | 0.0794           | 1.2         | 0.0792           | 2.8         | 21.8083    |
| 126      | 0.0452           | 1.4         | 0.0444           | 4.5         | 0.0422           | 32.1        | 25.8203    |
| 127      | 0.0747           | 1.1         | 0.0735           | 1.2         | 0.0733           | 2.5         | 20.3390    |
| 128      | 0.0507           | 1.0         | 0.0499           | 1.3         | 0.0497           | 4.1         | 26.1153    |
| 129      | 0.0589           | 1.3         | 0.0579           | 4.0         | 0.0560           | 28.6        | 21.0342    |
| 131      | 0.0644           | 1.1         | 0.0634           | 2.0         | 0.0626           | 9.9         | 38.6163    |
| 132      | 0.0902           | 1.2         | 0.0886           | 1.3         | 0.0884           | 2.6         | 19.3081    |
| 133      | 0.0537           | 1.1         | 0.0528           | 1.7         | 0.0524           | 7.5         | 0.0364     |
| 134      | 0.0721           | 1.1         | 0.0709           | 1.3         | 0.0707           | 3.8         | 10.1266    |
| 135      | 0.0861           | 1.0         | 0.0851           | 1.2         | 0.0849           | 2.4         | 19.6963    |
| 49       | 1.920            | 1.7         | 1.884            | 2.5         | 1.850            | 11.9        | 0.0097     |
| 51       | 1.900            | 1.5         | 1.869            | 1.9         | 1.890            | 7.9         | 0.6159     |
| 52       | 1.880            | 1.5         | 1.843            | 1.6         | 1.870            | 4.9         | 2.1848     |
| 54       | 1.820            | 1.5         | 1.788            | 1.6         | 1.810            | 5.0         | 2.3290     |
| 59       | 1.910            | 1.5         | 1.877            | 1.9         | 1.890            | 8.4         | 1.7260     |
| 61       | 1.870            | 1.5         | 1.834            | 1.6         | 1.870            | 3.9         | 2.3066     |
| 62       | 1.890            | 1.8         | 1.851            | 3.7         | 1.740            | 16.9        | 0.0205     |
| 67       | 1.720            | 1.6         | 1.694            | 1.8         | 1.710            | 6.6         | 1.7204     |
| 68       | 1.800            | 1.6         | 1.764            | 1.5         | 1.790            | 3.6         | 1.4337     |
| 69       | 1.760            | 1.6         | 1.730            | 1.5         | 1.760            | 3.6         | 2.3380     |
| 70       | 1.740            | 1.5         | 1.714            | 1.7         | 1.740            | 6.1         | 2.4390     |
| 71       | 1.730            | 1.5         | 1.705            | 1.5         | 1.730            | 3.4         | 2.1496     |
| 72       | 1.810            | 1.4         | 1.783            | 1.6         | 1.810            | 4.9         | 2.4072     |
| 73       | 1.760            | 1.6         | 1.730            | 1.5         | 1.760            | 3.4         | 2.0391     |
| 74       | 1.770            | 1.4         | 1.738            | 1.5         | 1.760            | 4.0         | 2.1136     |
| 78       | 1.770            | 2.7         | 1.707            | 12.3        | 1.180            | 28.4        | 2.0330     |
| 79       | 1.770            | 1.5         | 1.736            | 1.4         | 1.760            | 3.6         | 2.4883     |
| 80       | 1.800            | 1.5         | 1.767            | 1.4         | 1.800            | 3.8         | 2.0067     |
| 136      | 0.0855           | 1.1         | 0.0841           | 1.6         | 0.0837           | 6.6         | 18.5042    |
| 137      | 0.0891           | 1.3         | 0.0871           | 1.7         | 0.0864           | 2.7         | 1.4572     |
| 140      | 0.787            | 1.0         | 0.0774           | 1.3         | 0.0772           | 2.9         | 6.0083     |
| 141      | 0.539            | 1.1         | 0.0530           | 1.7         | 0.0527           | 7.8         | 4.0851     |
| 142      | 0.857            | 1.1         | 0.0842           | 1.3         | 0.0839           | 2.7         | 29.0030    |
| 87       | 1.780            | 1.1         | 1.748            | 1.5         | 1.780            | 4.0         | 0.0258     |
| 88       | 1.734            | 9.0         | 1.705            | 2.2         | 1.730            | 4.3         | 0.0010     |
| 89       | 1.799            | 1.2         | 1.766            | 1.6         | 1.790            | 4.2         | 1.9761     |
| 90       | 1.775            | 1.1         | 1.743            | 1.5         | 1.770            | 3.5         | 1.8203     |
| 91       | 1.764            | 1.2         | 1.732            | 1.5         | 1.760            | 3.8         | 1.7589     |

## X. FAILURE ANALYSIS

Many failure analyses were performed on failed capacitors and developmental test samples throughout the program. The majority of the test failures were catastrophic breakdown, which was induced by extreme power losses and overheating. Failed capacitors normally were recognized by large measured DF, low DC resistance, or by blown fuses in the life test apparatus.

### DEVELOPMENTAL TEST SAMPLES

#### Termination Variation

During the developmental work, many metallographic specimens of the flame sprayed terminations were prepared. Examination revealed unevenness of the winding and severe variations in the thickness of the flame sprayed coating. These variations were caused by runout of the winding.

Two samples were examined after pulse testing at high currents. One sample had failed after only a small number of pulses. The second sample had been subjected to  $400 \text{ A/cm}^2$  for  $10^5$  pulses and additional higher currents. At 400X magnifications no significant differences could be discerned. To distinguish any differences, a much more extensive analysis, e.g., with the scanning electron microscope, will be necessary.

#### Encasement Leaks

During initial exposure to elevated temperatures, some capacitors developed minute oil leaks. The number of leaks was about evenly divided between the two sizes of cases. The leaks were located at the soft solder joint between the outside of the feedthrough and the tubular case. The leaks were repaired easily by carefully reheating the solder joint. The problem was at least partly caused by inadequate tinning of the surfaces preparatory to the sealing operation and was experimental in nature.

### Insufficient Impregnant Penetration

During some of the dissections of failed capacitors, it was noticed that the capacitor sections had not been completely impregnated. The windings appeared to be so tight that the dioctyl phthalate did not penetrate the winding. Only the first few outer layers of winding were wetted. The remainder of the section appeared to be dry.

### LIFE TEST SAMPLES

Failures during the life test were all catastrophic. Examination revealed severe breakdown of the dielectric film. Generally the burned areas were large. The breakdowns apparently were caused by overheating. The overheating accrued because of the large power dissipation in the capacitor. Tests at elevated temperatures add to the problem.

### CORONA TEST SAMPLES

The capacitors were tested for the existence of corona at 40 VAC plus 0 to 500 VDC. The 40 VAC was applied first. The failures were catastrophic and primarily the 2  $\mu$ F capacitors. In several instances, the cases were ruptured.



## XI. CONCLUSIONS

### TERMINATIONS

Many two-metal terminations were compared with all-babbitt terminations. The two-metal combinations were aluminum-babbitt, tin-babbitt, and zinc-babbitt. The results showed that the resistance of the all-babbitt terminations was lower than any of the two-metal combinations. Furthermore, the variation in resistance was smaller. None of the two-metal combinations tested appeared to be better than babbitt alone.

The results of pulse testing flame sprayed babbitt terminations demonstrated that low resistivity is required for long life and reliability. The low resistivity was obtained by controlling the flame spraying process. Particularly, fixing the gun-to-work distance and predetermining the spraying time. Typically, low resistivity terminations did not exhibit any significant degradation after 100,000 pulses at  $400 \text{ A/cm}^2$ . At larger currents of 600 and  $800 \text{ A/cm}^2$ , life time was reduced but still substantial.

### INFANT MORTALITY

Many failures occurred during initial tests. Specifically, low capacitance, high DF, and short circuit on application of DC voltage during DC resistance measurements (IR). The latter were the result of film defects in conjunction with the high electric field used. Since none of the capacitors underwent the usual tests to screen out the weak units, except clearing at 600 VDC, the initial failures are attributed to infant mortality.

### LOW TEMPERATURE

The number of failures due to low temperature exposure was the same for both the  $0.1 \mu\text{F}$  and  $2 \mu\text{F}$  capacitors. The most failures were from the initial exposure of  $-3^\circ\text{C}$ . Additional failures occurred after  $-55^\circ\text{C}$  and one failure at  $25^\circ\text{C}$ . None occurred after  $125^\circ\text{C}$ . These failures were the result of breaking of the electrical connection between the flame sprayed termination and the metallized film. It may be rate sensitive, since no failures were attributed to temperature cycling, which also involved a low-temperature exposure.

## LIFE TEST

The principal failures during life test were due to breakdown. The breakdowns were attributed to overheating caused by excessive power dissipation. Testing at elevated temperatures intensified the problem.

The overheating can be understood from the following simple calculation. For a typical 2  $\mu\text{F}$  capacitor, the capacitance and DF at 10 kHz and 25°C is

$$C = 1.880 \mu\text{F}$$

$$\text{DF} = 0.041$$

The

$$\text{ESR} = \text{DF} \times X_c = 0.041 \times 8.47 = 0.35\Omega$$

At 20 VAC

$$I_{AC} = \frac{\text{VAC}}{X_c} = \frac{20}{8.47} = 2.36 \text{ A}$$

The power loss is then

$$P_L = I^2 R = 1.95 \text{ watts}$$

Under these conditions, the temperature will rise rapidly. Further, the DF increases with increasing temperature, and the power loss will increase further. At 20 VAC, the 2.0  $\mu\text{F}$  capacitors, even at room ambient, will fail within a short time.

Similar calculations for the 0.1  $\mu\text{F}$  capacitors show a power dissipation typically of about 0.1 watt, which is very small and of no consequence.

Some degradation occurred during the life test, since some of the survivors at elevated temperatures acquired a high DF after 1000 hours of operation.

## SUGGESTIONS AND RECOMMENDATIONS

A variety of failures occurred throughout the program. Some appeared to be infant mortality. Thus a need exists for screening tests to eliminate weak parts. In addition, the quality of the 6  $\mu\text{m}$  KF film is quite variable. Obviously, a better film is wanted.

Some additional work is needed on the impregnation technology as well as on the effects of low temperature and operation at elevated temperatures for long periods. The low temperature failures appeared to be rate sensitive and should be proven. Some degradation occurred during the life test. The failure mechanism should be established to achieve long life time and reliability.

As pointed out, the dissipation factor for KF film is quite large and variable with temperature. For AC applications, therefore, the large DF is critical. The consequent power loss must be thoroughly reviewed for each application.



## XII. REFERENCES

1. Robert D. Parker, Technological Development of High Energy Density Capacitors, NASA CR-124926, February 1976.
2. Joseph A. Zelik and Robert D. Parker, Technological Development of Cylindrical and Flat Shaped High Energy Density Capacitors, NASA CR-135286, December 1977.
3. W. E. Ballard, Metal Spraying and Sprayed Metal, Charles Griffin and Company Limited, 1948.

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### XIII. ACKNOWLEDGEMENTS

Special thanks are due Mr. Donald P. Feldman who did the automated testing. Mr. Allan E. Lange consulted on testing and data processing. Mr. Robert D. Gourlay developed the apparatus for the extended frequency measurements. Mr. A. N. Muller of Plasma Coatings, Gardena, CA, gave technical assistance and flame sprayed the capacitors used for this program.

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## APPENDIX I - STATEMENT OF WORK

### PREFACE TO EXHIBIT "A"

#### 1.0 BACKGROUND

During FY1975 and FY1976 2  $\mu$ F, 500 VDC ultra lightweight capacitors with energy densities greater than 0.1 J/g were developed under NASA contracts NAS3-18925 and NAS3-20090 with Hughes Aircraft Company. The weight of these capacitors are approximately one-tenth of the weight of comparable capacitors presently available for these operating conditions.

Under these contracts a life test for 2500 hours at room temperature was done. No testing or operations were performed at either extreme ambient or operational conditions. Therefore, to ascertain the full operating capability of these capacitors more extensive testing is needed. The proposed work is to test and operate these capacitors under extreme environmental and operational conditions to determine their operational limits. Part of the tests and test procedures used come from MIL-C-39022C and MIL-STD-202E.

#### 2.0 OBJECTIVE

The objective of this investigation is to build and test high energy density capacitors made from metalized polyvinylidene fluoride films.

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EXHIBIT "A"

1.0 SCOPE OF WORK

The contractor shall provide the necessary personnel, facilities, services, and materials to perform the work described below.

2.0 SPECIFIC TASKS

2.1 TASK 1 - Procedures

The procedures documented in NASA CR-135286 shall be employed in this work. Effort shall be expended on the following end termination investigation as described below.

2.1.1 Using 6 micron PVF2 metallized film scraps from previous contracts, the contractor shall fabricate, in his facility, ten termination resistivity samples of each of the following combinations:

2.1.1.1 Flame sprayed first with 1 mil minimum thickness aluminum oversprayed with Babbitt "A" metal as per "New Process" referred to in the Contractor's technical proposal, figure 3-3, incorporated herein by reference.

2.1.1.2 Flame sprayed first with 1 mil minimum thickness tin, oversprayed with Babbitt "A" metal as per "New Process" referred to in technical proposal figure 3-3.

2.1.1.3 Flame sprayed first with 1 mil minimum thickness zinc, oversprayed with Babbitt "A" metal as per "New Process" referred to in Technical proposal figure 3-3.

2.1.1.4 Flame sprayed with Babbitt "A" metal as per "New Process" referred to in technical proposal figure 3-3.

2.1.2 Subject five each of these samples (total 20) to  $400 \text{ A/cm}^2$  current pulses  $10^5$  times. Measure termination resistance at least prior to and at the end of the test. This test shall be performed like the test for figure 3-3 (technical proposal).

- 2.1.3 The contractor shall submit all samples, both tested and untested, to the NASA PM, with the end termination procedure, for approval prior to going on to Task 2.
- 2.1.4 Any deviations from the procedures documented in NASA CR-135286 shall be submitted to the NASA Program Manager prior to proceeding with Task 2.

## 2.2 TASK 2 - Fabrication

- 2.2.1 The contractor shall use the procedure approved in Task 1 with the following guidelines:
  - 2.2.1.1 Fabricate capacitors rated 2  $\mu$ F, 500 VDC, 5A AC 10 kHz to perform Tasks 3, 4, 5, 7 and 8 (minimum 130).
  - 2.2.1.2 Fabricate capacitors rated 0.1  $\mu$ F, 500 VDC, 0.25A AC 10 kHz to perform Tasks 3, 4, 5, 7 and 8 (minimum 130).
  - 2.2.1.3 All the above mentioned capacitors shall be fabricated from one PVF2 6 $\mu$  thick film roll. All unused metallized PVF2 shall be packaged and shipped to NASA LeRC., Attn: PM.
  - 2.2.1.4 Additional capacitors shall be fabricated to monitor the fabrication process. At least one representative sample of each days production lot shall be sent to the NASA PM, no later than ten working days after the run.
  - 2.2.1.5 Only the winding machine with tension controls constructed under contract NAS3-20090 shall be used for this task.

NOTE: The units manufactured as a lot during a particular day shall be distributed between Tasks 4, 5, 7 and 8.

## 2.3 TASK 3 - Capacitor Characteristics

- 2.3.1 For each of the capacitors constructed in Task 2, the contractor shall provide the following information:
  - 2.3.1.1 Capacitance versus frequency at a temperature of 25°C. All capacitors shall be measured at 60 Hz, 1.0 kHz and 10 kHz. In addition, twenty capacitors of each size shall be measured at 10 Hz and 100 kHz.

- 2.3.1.2 Dissipation factor versus frequency at a temperature of 25°C. All capacitors shall be measured at 60 Hz, 1.0 kHz and 10 kHz. In addition, twenty capacitors of each size shall be measured at 10 Hz and 100 kHz. Any capacitors which have a dissipation factor at 1.0 kHz greater than 10 percent of the norm shall be rejected from further use and replaced with additional units from Task 2.
- 2.3.1.3 Direct current resistance at 500 VDC and a temperature of 25°C.
- 2.3.1.4 Corona Information - Using a corona test set, each of the capacitors shall be tested for the existence of corona at voltages up to 500 VDC and 40 VAC, 60 Hz applied simultaneously. The test circuit sensitivity shall be 5 picocoulombs minimum for the 0.1 µF capacitors and 80 picocoulombs minimum for the 2.0 µF capacitors. With the 40 VAC, 60 Hz applied to the capacitor under test the DC voltage shall be slowly increased from 0 to 500 VDC. If continuous corona counts occur below 500 VDC, the corona inception voltage shall be recorded. With the 500 VDC and 40 VAC, 60 Hz applied, a 30 second long corona spectrum of continuous counts shall be made for at least five intervals. A background count (noise) over the same interval shall also be recorded.
- 2.3.1.5 Capacitor Identification - The contractor shall mark each capacitor with a code number in smear resistant ink. The character dimension shall be at the discretion of the contractor. The following information on each capacitor shall be furnished on a separate list referenced to the code number:
1. Capacitance at 25°C
  2. Capacitance tolerance
  3. DC working voltage
  4. AC peak rated voltage at 10 kHz
  5. Date code

NOTE: Twenty each of the two capacitor sizes tested under 2.3.1.1 and 2.3.1.2 over the extended range of frequency shall be divided equally between Task 4 ( $-55^{\circ}\text{C}$ ), Task 5 (500 and 600 volt) and Task 7. The remaining capacitors tested over a limited frequency range shall be used for the remaining units in Task 4, 5, and 7 and all units of Task 8.

## 2.4 TASK 4 - Low Temperature Tests

### 2.4.1 $-55^{\circ}\text{C}$ Tests

The contractor shall place 20 of the  $2\ \mu\text{F}$  and 20 of the  $0.1\ \mu\text{F}$  capacitors constructed in Task 2 in a chamber maintained at  $-55^{\circ}\text{C}$ . A potential equal to 500 VDC shall be applied to each capacitor at this temperature for 48 hours. The voltage shall be applied to each capacitor through its individual current-limiting resistor of such a value to limit the charging current to 50 mA. The air within the conditioning chamber shall be circulated.

### 2.4.2 $-3^{\circ}\text{C}$ Test

The contractor shall place 20 of the  $2\ \mu\text{F}$  and 20 of the  $0.1\ \mu\text{F}$  capacitors constructed in Task 2 in a chamber maintained at  $-3^{\circ}\text{C}$ . A potential equal to 500 VDC shall be applied to each capacitor at this temperature for 48 hours. The voltage shall be applied to each capacitor through its individual current-limiting resistor of such a value to limit the charging current to 50 mA. The air within the conditioning chamber shall be circulated.

### 2.4.3 Measurements

At the conclusion of the 48 hour periods in Task 4(a) and 4(b), capacitance, insulation resistances, and dissipation factor (DF) shall be measured for each of the 80 capacitors at respective  $-55^{\circ}\text{C}$  or  $-3^{\circ}\text{C}$  temperature. The capacitance and insulation resistance shall be measured also at temperatures of  $25^{\circ}\text{C}$  and  $125^{\circ}\text{C}$ . The  $-55^{\circ}\text{C}$  and the  $-3^{\circ}\text{C}$  temperature measurements shall be made before the capacitors are removed from the conditioning chambers. After the tests, all these capacitors shall be examined for opens, shorts, and the corona information as in 2.3.1.4 above.

## 2.5 TASK 5 - Life Test at Elevated Temperature

The contractor shall subject 40 2  $\mu$ F and 40 0.1  $\mu$ F capacitors constructed in Task 2 to the following:

### 2.5.1 Operating Test Conditions

The 80 capacitors for this task shall be divided into two groups for testing as follows:

2.5.1.1 Twenty each of the 2  $\mu$ F and 20 each of the 0.1  $\mu$ F capacitors shall be tested for corona in accordance with 2.3.1.4, except that the maximum DC voltage shall be 600 VDC. After the corona test the capacitors shall be placed in a chamber where the ambient temperature is such that the capacitor cases are maintained at 125°C while the capacitors are operating at 600 VDC 20 VAC 10 kHz. The capacitor temperature shall be monitored by a thermocouple attached to one of the device cases. In addition, the temperature along the entire length of the case of each capacitor shall be determined by means of temperature indicating decals or paints. The life test shall run for 10,000 hours.

2.5.1.2 Twenty each of the 2  $\mu$ F and 20 each of the 0.1  $\mu$ F capacitors shall be placed in a chamber where the ambient temperature is such that the capacitor cases are maintained at 125°C while operating at 500 VDC, 20 VAC 10 kHz. The capacitor temperature shall be monitored by a thermocouple attached to one of the device cases. In addition, the temperature along the entire length of the case of each capacitor shall be determined by means of temperature indicating decals or paints. The life test shall run for 10,000 hours.

### 2.5.2 Measurements

#### 2.5.2.1 During Life Tests:

The dissipation factor (DF) capacitance, and the insulation resistance of each capacitor shall be measured at the temperature of 125°C. The tests shall be interrupted as a minimum at 1000, 2500, 5000 and 7500 hours, to determine capacitor condition, by measuring the

various electrical properties over the limited frequency range as described in 2.3.1.1; 2.3.1.2; 2.3.1.3 and 2.3.1.4. During these measurements the life test voltages shall be removed from the capacitor terminals.

2.5.2.2 After 10,000 Hours of Life Test:

The capacitance, dissipation factor, insulation resistance and corona shall be measured at a temperature of 25°C. The corona shall be measured as in 2.3.1.4 except that the maximum voltage for the forty capacitors tested in 2.5.1.1 shall be 600 VDC + 40 VAC, 60 Hz applied simultaneously. The capacitance and dissipation factors shall be measured at 60 Hz, 1.0 kHz and 10.0 kHz.

2.6 TASK 6 - Reserved

2.7 TASK 7 - Thermal Cycling

The contractor shall subject 25 2  $\mu$ F and 25 0.1  $\mu$ F capacitors, a total of 50 capacitors, constructed in Task 2 to the thermal cycling test conditions listed in the table below. A total of five cycles shall be performed continuously. Separate chambers shall be used for the extreme temperature conditions of steps 1 and 3. The capacitors shall not be subjected to forced circulating air while being transferred from one chamber to another. The capacitors shall be mounted in the chambers such that there are no obstructions to the flow of air across and around the capacitors. At the conclusion of the five thermal cycles, the insulation resistance, capacitance and dissipation factor from 60 Hz to 10 kHz, and corona information shall be measured at a temperature of 25°C.

THERMAL-CYCLING TEST CONDITIONS

| <u>STEP</u> | <u>TEMPERATURE</u> | <u>TIME</u>      |
|-------------|--------------------|------------------|
| 1           | -55°C              | 30 minutes       |
| 2           | 25°C               | 10 to 15 minutes |
| 3           | 125°C              | 30 minutes       |
| 4           | 25°C               | 10 to 15 minutes |

## 2.8 TASK 8 - Vibration Tests

The contractor shall subject 25  $2\ \mu\text{F}$  and 25  $0.1\ \mu\text{F}$  (a total of 50) capacitors constructed under Task 2 to simple harmonic motion in the frequency range of 10 Hz to 2000 Hz. The vibration amplitude shall be either 0.06 inch double amplitude (maximum total excursion) or 20 g (peak) whichever is less. The capacitors shall be rigidly mounted by the body to a vibration-test apparatus. The axial-wire lead terminals shall be secured 0.5 inch from the case. During the tests a DC potential of 250 V shall be applied between the terminals of the capacitors. Each capacitor shall be vibrated four hours each in two mutually perpendicular directions (total 8 hours), one parallel and the other perpendicular to the cylindrical axis. The vibration frequency shall be varied logarithmically between limits of 10 Hz and 2000 Hz. The entire frequency range of 10 Hz to 2000 Hz and return to 10 Hz shall be traversed in 20 minutes.

This cycle shall be performed 12 times in each of the two mutually perpendicular directions (total 24 times), so that the motion shall be applied for a total period of eight hours.

Measurements: During the last cycle in each direction, an electrical measurement shall be made to determine intermittent contacts of 0.5 ms or greater duration, or open, or permanent short circuiting.

After the vibration test the capacitance and dissipation factor from 10 Hz to 10 kHz, insulation resistance, corona information shall be measured.

## 2.9 TASK 9 - Failure Analysis

The contractor shall analyze all capacitors that failed to determine the nature and cause of failure. The contractor shall separate failed parts into the failure modes that include insulation breakdown, corona, leakage, clearing, termination and mechanical. Upon approval by the NASA program manager the contractor shall proceed to analyze one capacitor of each group. The analysis shall, as a minimum, include photographs that illustrate the capacitor's internal damage, and examinations and tests to determine the point of initial failure together with engineering data substantiating the nature and cause of the failure.

## 2.10 TASK 10 - Delivery

Except as required in Task 2, all test samples shall be the property of the Government. After completion of the technical effort and submission of the final report, the NASA contracting officer may require all or part of the capacitors constructed



under Task 2 to be shipped to Lewis Research Center. Dissected capacitors shall be protected from damage after the contractor has completed his analysis. The winding machine with tension controls shall be boxed and shipped to LeRC. In addition, the two life test circuits used in Task 5 shall be shipped to LeRC.

#### 2.11 TASK 11 - Informal Presentation

At the completion of the technical work performed under this contract, the contractor shall make an informal oral presentation of the results at Lewis Research Center.

#### 2.12 TASK 12 - Reporting Requirements

Technical, financial, and schedular reporting shall be in accordance with Reports of Work attachment, which is hereby made a part of this contract.

2.12.1 The monthly report submission date shall be no more than 20 calendar days after the closing date of the contractor's accounting month.

2.12.2 The number of copies to be submitted for each monthly report is as follows:

2.12.2.1 A maximum of 30 copies of the monthly Technical Progress Narrative, including all new data originating from Tasks 1, 2, 3, 4, 5, 7.

2.12.2.2 A maximum of 8 copies of the contractor's Financial Management Report (NASA Form 533P).

2.12.2.3 The reporting categories to be reported on in the contractor's initial and monthly reports shall be:

|                 |   |
|-----------------|---|
| Task 1          | Procedures                              |
| Tasks 2 - 10    | Fabrication and Delivery                |
| Task 3          | Capacitor Characterization              |
| Tasks 4 - 5 - 7 | Testing                                 |
| Task 8          | Vibration Tests                         |
| Task 9          | Failure Analysis                        |
| Tasks 11 - 12   | Presentation and Reporting Requirements |

Report manhours and dollars by Task, total cost and fee. Column 8a of NASA Form 533M shall contain the cost estimates for the month following that reported in column 7c. Column 8b shall contain the cost estimates for the month following that reported in column 8a.



